With kindest regards.

Mr. E. H. Cunningham-Craig.

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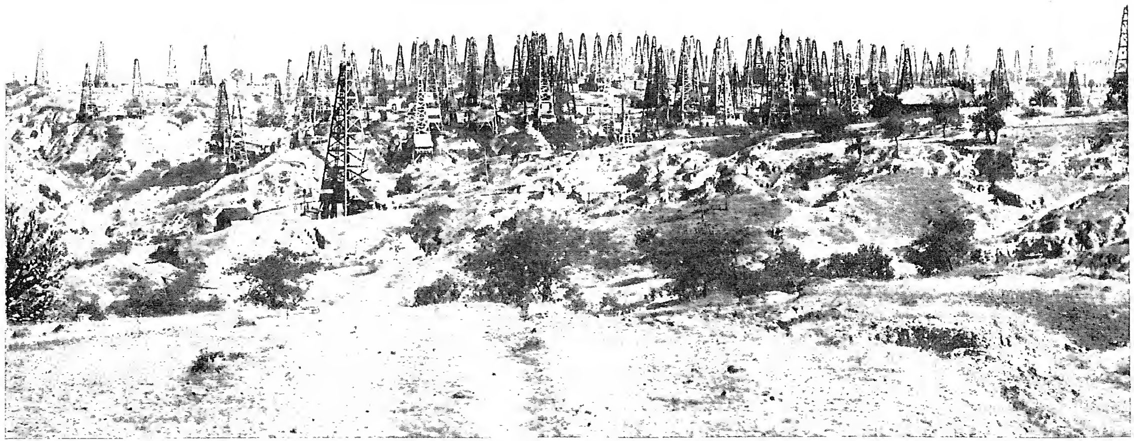

Photo. by M. Croudiansky

General View of the Twingon Oil-Reserve, Yenangyoung Field, Burma.

OIL-FINDING

AN INTRODUCTION TO THE GEOLOGICAL STUDY OF PETROLEUM

BY

E. H. CUNNINGHAM CRAIG, B.A., F.G.S.

LATE OF H.M. GEOLOGICAL SURVEY

WITH AN INTRODUCTION

BY

SIR BOVERTON REDWOOD, BART.

ADVISER ON PETROLEUM TO THE ADMIRALTY, HOME OFFICE, AND INDIA OFFICE

CONSULTING ADVISER TO THE COLONIAL OFFICE

ILLUSTRATED

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EDWARD ARNOLD

1912

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TO

ARTHUR SANKEY REID

IN GRATEFUL MEMORY

OF HOW MUCH I OWE TO HIM

CONTENTS

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INTRODUCTION

BY

SIR BOVERTON REDWOOD, BART.

Mr. Cunningham Craig's "Oil-finding" is a laudable and successful attempt to deal with a subject which has hitherto received far too little attention, and those who have within recent years had occasion to deplore the waste of money which has resulted from the publication of injudicious reports on lands presumed to be oil-bearing, and from the unscientific manner in which drilling operations have been conducted, will regret that this book was not published long ago.

The author points out that the foundation of the successful petroleum enterprise must be laid by the geologist rather than by the engineer, and he states that the present work has been written for geologists, and especially for young geologists; but it may be added that, to a large extent, the views expressed are couched in language so free from technicalities that the work may be studied with profit by a far wider circle, including, in fact, all those who are interested in the petroleum industry, either in an administrative capacity, or as investors.

With the aid of this book, and the exercise of common sense, those who contemplate investment in petroleum undertakings may place themselves in a position to form an independent opinion as to whether the technical data given in a prospectus are adequate, and are such as to justify the appeal for subscriptions. Similarly, the shareholders in petroleum projects which are of an exploratory nature, or in which the work of exploitation is passing through the earlier stages, may learn to interpret reports of progress which at present they find unintelligible. Not only would this enlightened judgment be of inestimable value to those who exercise it, but it would incidentally provide the most effective remedy for an evil to

which the author alludes, viz. that of the "popular safeguarded report," which in lieu of being a record of facts and legitimate deductions, seeks to create a highly favourable impression by means of a few well-rounded sentences, in which the weak points of the case are ignored and superlatives are prominent. It is obvious that the possession by those to whom such reports are intended to appeal of such knowledge as Mr. Cunningham Craig's book imparts, would very soon result in rendering this procedure worse than useless, and in this connexion it should be borne in mind that the expert is not alone to blame, for, as the author points out, it not infrequently happens that his views are quoted in a form in which they do not correctly convey what he stated.

The earlier portion of the work, as the author himself admits, deals with many theoretical questions of a controversial character, and it is not to be expected, nor does he himself anticipate, that his strongly expressed opinions will in all cases be accepted; but this does not detract from the value of the work, and in fact it may be said to enhance it if, in accordance with the avowed intention of the author, the further study of these questions is thereby stimulated.

Mr. Cunningham Craig in his concluding remarks modestly disclaims originality for the last two chapters of this work, and further indicates elsewhere that these chapters are intended for beginners, but the dominant feature of the whole work may be said to be the boldness and originality of treatment of the subject, and there is much in the advice which he gives to beginners which may be studied with advantage by those who have had lengthy experience.

B. R.

AUTHOR'S PREFACE

This little book does not pretend to be a treatise upon Petroleum, nor even to exhaust the particular circumscribed branch of the subject with which it deals.

Petroleum and the search for petroleum have recently bulked largely in the public eye. Discoveries all over the world have proved the wide-spread occurrence of mineral oils; the demand for them has stimulated, and to some extent created, active search for and development of petroliferous areas, and it has become increasingly evident, not only to the scientific, but also to the commercial world, that it is to the geologist rather than to the engineer that one must look in the first instance if successful results are to be achieved.

Much has been written in late years upon the subject of petroleum, but very little that is of service to the practical field-geologist. Speculative and more or less theoretical work by indoor students of the subject is available in abundance, while the practical work of oilfields has been in most cases conducted by what have been known by a curious distinction (too frequently heard even now-a-days), as "practical" as contrasted with, or even opposed to, "scientific" men; consequently many facts of vital importance, and many generalizations reached by long experience never see the light in publications accessible to the scientific student of the subject. It is hardly too much to say that so much nonsense has been written and published about oil, or particular oilfields, that many vague but essentially erroneous ideas are current, if not actually accepted. In many otherwise excellent works on the subject geology is dismissed in a few carefully guarded and colourless paragraphs, or at the best in a chapter or two, while such data as statistics are given a prominence which is more acceptable to the commercial than to the scientific world. Similarly, geographical data are set forth at length, and geological maps are rarities.

It is to fill up a few of the blanks left by previous authors that this book has been written; it is for geologists, and more especially for young geologists, in the hope that it may prove of value to those who may have to undertake exploration work for a mineral which is not naturally familiar to the stay-at-home Briton.

The author is quite aware that his knowledge of petroleum is limited, but in the few not unimportant fields that have come within his ken a thorough and intimate knowledge has been obtained, and he has been able to study the subject in these fields in a manner for which neither the "practical" prospector, nor field-manager, nor the peripatetic expert, has time. Also in these few fields he has had an opportunity not only of observing almost all the different environments in which petroleum occurs, and many different grades and classes of oils, but also of having brought to his notice nearly every kind of mistake that prospectors or experts with a merely nodding acquaintance with geology can make in attempting the development of a new field.

Theoretical matters will perforce have to be treated of, or touched on, here and there, but for the most part the notes that follow are a record of *facts*, slowly and often laboriously collected during detailed geological field-mapping, with the conclusions to which these facts inevitably point. If the author has taken a somewhat uncompromising standpoint with regard to some of the main theoretical questions still under controversy, it is largely with the intention of stimulating discussion upon them, and the search for and bringing forward of new and incontrovertible evidence.

It is assumed that the reader is conversant with the simple technical terms employed in field-geology.

I am indebted to Messrs. Robert Lunn and J. Ness, of H.M. Geological Survey, for help in the preparation of the illustrations, and my thanks are due to Messrs. C. S. Rogers, M. Crouliansky, G. B. Reynolds, S. Lister James, and Professor J. Cadman, who have kindly allowed me to publish photographs of geological interest which they have taken.

E. H. C. C.

April, 1912.

LIST OF PLATES

OIL-FINDING

CHAPTER I

THE ORIGIN OF PETROLEUM

It has been the custom in treatises upon petroleum, the one bright exception being the work of Engler and Hofer, to regard the origin of the mineral as an interesting academic but unimportant question, which is fully dealt with when the various theories have been stated, the least popular summarily dismissed, and a few pages of carefully guarded general statements written round about without ever touching the root of the matter.

That this unsatisfactory state of things has arisen from lack of definite information on definite points is the misfortune rather than the fault of the authors, but all geologists will agree that to leave a question of such vital importance unsettled is to blindfold the student or prospector at the very start. How, if one does not know, or cannot prove, from what material and under what conditions petroleum is formed, can one tell where to look for it or ever be confident as to its presence beneath the surface?

This question of origin, in fact, absorbs and includes nearly every other question as to the occurrence, distribution, and winning of oil.

The theories that have been brought forward from time to time to account for the origin of petroleum and its congeners divide themselves naturally into two classes, which again may be subdivided as follows:—

A. Inorganic Origin	1. Hypogene Causes. 2. Volcanic Action.
B. Organic Origin	1. From Animal Matter. 2. From Vegetable Matter.

A. Theories of the **inorganic origin** of petroleum are essentially the ideas of chemists and indoor-students of the subject. They are founded on assumptions and built up by theoretical considerations, none of which have been tested by application to actual facts and conditions as observed in nature.

(1) The most ingenious of the *hypogene* theories suggests the origin of petroleum by the condensing and isomerization of hydrocarbons formed by the action of water upon supposititious masses of metallic carbides deep within the crust of the earth. Such vague hypotheses are almost invariably rejected nowadays, and it is needless to enter upon a detailed examination of the various arguments *pro* and *con*. The conditions under which petroleum is found in nature furnish sufficient grounds for the dismissal of any theory involving a deep-seated origin.

(2) *Volcanic action* has occasionally been suggested to be responsible in some ill-defined way for the occurrence of petroleum. At first sight there appears to be some direct evidence favourable to this idea. For instance, oilfields are found in many parts of the world at no great distance from, and even running parallel with, lines of volcanic activity. Japan and Sakhalin, Mexico, Burma, and the West Indies are cases in point. Again, mud-volcanoes of solfataric type, an evidence of undoubted volcanic action usually in the obsolescent stage, have been confused with mud-volcanoes due to the discharge of gas from underlying oil-rocks. These are two entirely different phenomena, but if no distinction be made between them it might be erroneously claimed that there is evidence of volcanic action in very many oilfields. When the question is examined in detail, it is seen that both the lines of volcanic activity and the structures which are conducive to the formation and storage of petroleum are merely separate and independent effects of the same cause. Volcanic lines are developed near to or along the margins of continental masses, or, more correctly, between continents and deep oceanic basins; that is to say, in belts where active earth-movement is taking place. Many oilfields also lie along belts where active earth-movements have been experienced, but there is no evidence to suggest that the vulcanicity and the formation of petroleum are essentially connected in any way. The

distribution of land and water may be vastly different now from what it was when active vulcanicity obtained; and it can frequently be proved that the oil was formed before vulcanicity commenced, and may have remained after all such action has ceased. Interesting evidence of this nature is to be obtained in Burma and Barbados.

To go into the matter more closely, it is difficult for a geologist to realize exactly what those authors who have promulgated the idea of a volcanic origin of petroleum really mean by "volcanic action." As evidence they bring forward the well-known cases of distillation caused by the intrusion of igneous rocks through such strata as the coal measures or the Scottish oil-shales—phenomena which are not necessarily connected with true volcanic action. That such local distillation has frequently taken place is proved by abundant evidence, and the igneous rock may be found to contain in small cavities soft or elastic bituminous compounds. In Fife and in the Karroo, South Africa, such evidence may be obtained.

These effects, however, are purely local, and no instance of such action on a large scale has been brought forward; the limits of the distilling action are usually well-defined. Even were such evidence on a large scale available, the occurrence of the bituminous compounds only demonstrates the presence of organic matters contained within the sedimentary strata so affected, and the igneous action cannot be considered the *origin*, but merely the process which has happened to call attention to the potentially bituminous nature of the strata.

That volcanoes themselves should produce petroleum has not been suggested, since in spite of the minute care with which volcanoes have been studied, no observer has obtained evidence favourable to such an hypothesis.

In no large and productive oilfields have igneous rocks, either intrusive or volcanic, been encountered to any considerable extent, and to use the term "volcanic action" in a vague sense to account for phenomena which are not associated with any such action is merely to beg the question, and at the same time to disregard a mass of relevant evidence which has been gradually accumulated ever since petroleum first became of commercial importance.

B. Organic Origin.—In considering the theories of the

formation of petroleum from organic matter it is necessary to examine a vast mass of evidence, chemical, geological, and experimental. The views of many experts are still undecided, and the relative importance of animal or vegetable matter as the material from which petroleum and petroleum compounds can be formed is a question that is handled very gingerly in recent publications. Yet, as stated above—and it cannot be stated too often and too strongly—unless we can make up our minds upon this question, the search for new oilfields must necessarily become to some extent a groping in the dark. Before asking himself if there is oil to be found in any district or locality, the geologist must consider why there should, or should not, be oil; how it could have reached such an environment, and whether it can be relied upon to be present, if drilled for. To enter into such enquiries without knowing from what material the oil has been formed, is to adventure upon a search with one eye bandaged.

The question is not merely of academic but of great practical importance, and it is in the author's experience that great sums of money have been fruitlessly thrown away by petroleum companies solely because those responsible for the selection of possible new fields to be tested had not mastered this first essential question of the origin of petroleum.

B (1) *Animal Origin.*—The theory that petroleum is formed by the decomposition or destructive distillation of animal matter entombed in the strata has many adherents at the present day. It has arisen largely from the wish to find a marine origin that will be acceptable to scientists. As oil occurs in sedimentary strata, and most sedimentary strata are to some extent at least marine in origin, there was a natural tendency to seek for some mode of origin for petroleum compatible with the manner of accumulation of ordinary sedimentary rocks.

The evidence upon which this theory rests is largely chemical, many chemists having conducted researches with the object of ascertaining whether oils with the characteristics of natural petroleum can be formed from animal matter.

Let it be granted at once that under conditions easily reproducible in a chemical laboratory animal matter of almost every kind can be decomposed and separated out into various classes of compounds, some of which can, when properly

treated, be converted into mixtures of oils closely resembling petroleum as found in nature.

The chemical processes can be expressed roughly and generally as, first, the elimination of nitrogen and nitrogen compounds, and then a destructive distillation of the fats to form mixtures of hydrocarbons. With the actual processes employed it is not necessary to deal in detail; the reader is referred to the work of Engler and Hofer and of others who have made the possibility of the extraction of oils from animal matter abundantly clear.

This possibility being accepted, many authors, pointing to the indubitable evidence of the former existence of living organisms among the strata in which petroleum is now found, seem to consider that further proof is unnecessary. Each author has probably his favourite class or order of organism which he would make responsible for the raw material in each particular oilfield of which he has special knowledge. Thus at one time or another almost every class of organism, from the fish of Mr. Winda, the Russian geologist, to the diatoms and foraminifera of the United States Geological Survey (California, Texas and Louisiana Oilfields) has had special attention drawn to it in this connection.

Sometimes the chemical theorists carry their speculations even further, and suggest that the characteristics of the oils formed, *e.g.* whether of paraffin or asphaltic base, may be determined by the nature of the raw material.

Of the geological evidence, however, little that will bear careful scrutiny has been adduced to support the animal-origin theory. A statement such as the following, "this series is oil-bearing, and at intervals throughout it the hard parts of animal organisms are found," seems to be regarded by many as sufficient evidence upon which to base a generalization of such enormous importance.

Again, the occurrence of oil in limestones is often brought forward as a clinching argument, even by authors who, perhaps in the next chapter, deal with the migration of petroleum through vast thicknesses of strata and its appearance naturally in the most porous rock available. "Here," one will say, "is a coral limestone formed chiefly of the debris of coral and other organisms often in the position of growth, and it is impregnated with petroleum," leaving it to be inferred that the oil has been

formed from the soft parts of the coral polyps, and oblivious of the fact that a similar argument might be made to apply to a recent beach, full of shell fragments and similarly impregnated, such as may be seen in many localities in the Island of Trinidad.

The geologist, however, demands more detailed and definite evidence; it is not enough for him to know where the oil is found, he must assure himself on many points, such as the lateral and vertical distribution of the petroleum in a geological series, the conditions under which the series has been deposited, the manner in which sufficient raw material to form the oil has been accumulated, and the process by which the oil has been concentrated and brought to its present position. When such questions are gone into carefully, one possibility after another is disposed of, and by a process of elimination an inevitable conclusion is finally reached.

In such enquiries the golden rule is *never to postulate or suggest any condition or any mode of deposition or accumulation which cannot be shown, or proved, to be actually in operation at the present day.* It is by the study of the present that the secrets of the past are revealed.

In justice to the chemical theorists it must be admitted that they have occasionally attempted to meet the objections of geologists by reference to actual facts. Samples of sludge or slimy mud containing organic matter more or less decomposed have been taken from harbours, estuaries, or mud-flats, analysed and distilled, and petroleum-like compounds in minute quantities, it is true, separated out. The fallacy lies in the assumption that these samples from the upper layers of the sludge are typical in chemical composition of the mass of slowly accumulating material beneath. The upper layers teem with animal life, no doubt, but there is a rapid change downwards. When a dredger is working in the sludge of a harbour or estuary, it will be observed by anyone who makes a study of the material removed that the lower layers differ very considerably in colour from the upper layers, and that at a depth of two or three feet almost all trace of organic matter, with the exception of the hard parts of mollusca, has disappeared. The change of colour is almost entirely due to the reduction of iron compounds, ferrous salts replacing ferric, and this process is effected principally by the decomposition of organic matter. The author

had occasion at one time to note day by day samples of the slowly accumulating fine sludge of Port of Spain Harbour, Trinidad. These samples were taken on the Government dredger, and a selection of them was analysed by Professor Carmody, Government Analyst of Trinidad. The environment is an ideal one for the accumulation of animal matter and its entombment in impervious argillaceous sediment. But in the specimens analysed the percentage of organic matter was infinitesimal, though the remains of the hard parts of mollusca were by no means uncommon. Such sludges will become in time blue clays, precisely similar to those which are so frequent among the Tertiary strata of Trinidad, and which, though they often contain rich molluscan faunas, are almost entirely free from organic matter.

It is doubtful, indeed, if it is ever possible for the soft parts of animal organisms to be entombed to any considerable extent among accumulating sediments. In seas and estuaries the waters and the upper layers of whatever sediment is being formed teem with life, but as each organism dies it is eaten or decomposed—in most cases it is certainly eaten alive. Its soft parts become absorbed into the bodies of living organisms, only its hard parts (and often not very much of them) go to swell the deposit of sedimentary material. Thus equilibrium is maintained; the mass of organic matter does not go on indefinitely increasing, but remains a practically constant quantity; the inorganic matter is continually being extracted by the living organisms from the water and the sediment brought into it by rivers and by denudation of the coast-line, and this inorganic matter, after a longer or shorter period in which it is part of a living organism, is being passed on to take its part in the formation of future strata.

Thus the first great difficulty that upholders of the animal-origin theory have to face is that of proving that animal matter can be entombed in sufficient quantity to account for the vast stores of petroleum contained in sedimentary strata. It is possible, of course, under special local conditions, to preserve and entomb the soft parts of animals, but throughout the geological record instances of such preservation are very few and far too insignificant to serve as evidence against the known facts as to the almost universal destruction or decomposition that overtakes each organism sooner or later.

To point to highly fossiliferous strata as proof that animal matter has been entombed in large quantities is to disregard facts for the sake of an attractive theory. The hard parts of diatoms and foraminifera cannot sink and become involved in a sedimentary deposit till the animal matter has been destroyed, and similarly nearly every fossil that is preserved in strata can be proved to have lost its soft parts before becoming incorporated in a bed that is being formed.

An interesting illustration of this process of nature may be studied in almost any fine argillaceous rock rich in fossil evidence; a clay for instance that has accumulated slowly and that now contains perfect specimens of the hard parts of mollusca, such as lamellibranchs with the two valves joined and closed or gasteropods. In such a case, if anywhere, it might be expected that entombment of animal matter might have taken place. But what do we find? Almost every perfect specimen bears the "death-mark" (Plate II), the small round hole drilled by the predatory gasteropod, which has fastened upon its victim, pierced its outer armour, and devoured its fleshy part. Fossiliferous clays in the Pegu Series of Burma, a series in which oil-bearing strata occur at intervals throughout a thickness of 4000 feet in some localities, afford very abundant evidence of this nature.

The most fossiliferous beds, however, are almost invariably littoral deposits in which there is a mixture of forms from deep and shallow water. Whether whole or fragmentary, many of the fossils show the death-mark, while the fragmentary nature of most specimens proves that they have been washed about the shore with every wave and tide long after they have lost all traces of their soft parts. The abundant evidence of crustacea and fishes, the scavengers of the sea, included in such beds serves to remind us that organic material is not wasted, is not rejected to pass with inorganic matter into the sediment, but is, so to speak, continually kept in circulation. "Eat and be eaten" is a law of nature, and from these little life tragedies of the mollusc we may realize the difficulty in the way of the accumulation of sufficient animal matter, a difficulty which the animal-origin theorists gloss over so lightheartedly.

Quite apart from this initial impossibility of proving a sufficient supply of raw material from which petroleum might

be formed, there is also much chemical evidence against the animal-origin theory.

It is only from the fatty parts of animal organisms that the petroleum could be formed, so it is only a portion, and often a very small portion, of the soft parts that can be utilised. The elimination of nitrogenous compounds and at the same time the preservation of the fats must be presupposed, and such an assumption may be said to beg the whole question. The theory is that the animal matter decomposes in such a manner that, before it is entombed, practically all nitrogenous matter has been removed (since only the merest traces of nitrogen compounds have ever been found in natural petroleum), and the preservative action of salt water has even been adduced to make such a retarded decomposition appear less improbable. But can we find any evidence of such a selective decomposition in nature? Are fats preserved, even in sea-water, while flesh is decomposed and dissipated as gases? Let any one who has studied the formation of guano, or who has been unfortunate enough to have the processes in the decomposition of a dead whale forced upon his senses, answer.

A very special and peculiar form of decomposition must be postulated, and furthermore, one that does not eliminate the sulphur content, since sulphur compounds are in many cases present in petroleum, sometimes in large quantity. The high pressures necessary to favour the formation of paraffin hydro-carbons from fats are inconsistent with conditions that will allow the escape of nitrogen in gaseous compounds, and as it is neither expedient nor justifiable to assume the existence of conditions of which we have no actual evidence in nature, much of the interesting laboratory evidence can only be regarded as experimental rather than explanatory.

Another difficulty which the animal-origin theorists have to encounter is the disposal of the phosphorous contents of the animal matter. This, of course, on the decomposition of the animal organisms naturally takes the form of phosphates. Now of all salts formed in nature the phosphates, whether of iron or calcium, or double and compound phosphates, are among the most difficult to dissolve and remove in solution. Hence, phosphatic beds or lines of phosphatic nodules may be expected near or among those beds where animal organisms have been most abundant. The phosphates indeed remain chiefly as, or

in, the hard parts of the organism when the softer parts have been decomposed or absorbed into the economy of other living organisms. The proportion of derived phosphates to animal fats is very high in nearly all marine and fresh-water organisms. If, then, we are to contend that the petroleum of our great oilfields is derived from animal matter, vast stores of phosphate must be present somewhere in the vicinity of the place where the oil has been formed. But we know of no great phosphatic deposits associated with oil-rocks or within the confines of oilfields.

This objection is partially met by the suggestion that the oil is formed in very minute quantities throughout very widespread deposits of enormous thickness, and has been gradually concentrated, migrating drop by drop to where it is now found; and as phosphates occur in small quantities in practically every rock, sedimentary or igneous, and in an oilbearing series as elsewhere, it may be claimed that the quantity of petroleum formed in any given area is not out of all proportion to the quantity of phosphates in that area. No calculations as to the proportion of phosphates to oil have been put before the scientific world as yet. The calculation, however, is simple. The area from which an oilfield can have derived its petroleum can be demarcated in many cases with considerable accuracy, the weight of oil in the field can be estimated, as has often been done, and the average phosphate content of the strata can be obtained by a series of analyses.

If fish, as has been suggested, are the source of origin of the petroleum, the proportion of phosphates to oil must be very high, and even if lower organisms are made to do duty as the source of raw material, the proportion of phosphate to animal fat is still large. It will be found that such an enormous mass of phosphatic material would have to be postulated as existing in the strata, that its presence would be continually demonstrated by bed after bed of nodules or masses, which would be of too great commercial value to have been overlooked.

It is unnecessary to allude to more of the practical difficulties which beset the animal origin theory when it is tested by reference to geological field evidence. To sum up, those who believe in an animal origin for petroleum have to call to their aid methods of accumulation of material of which we have no evidence, and chemical processes easily arranged for in a laboratory, but of, to say the least, very doubtful occurrence in

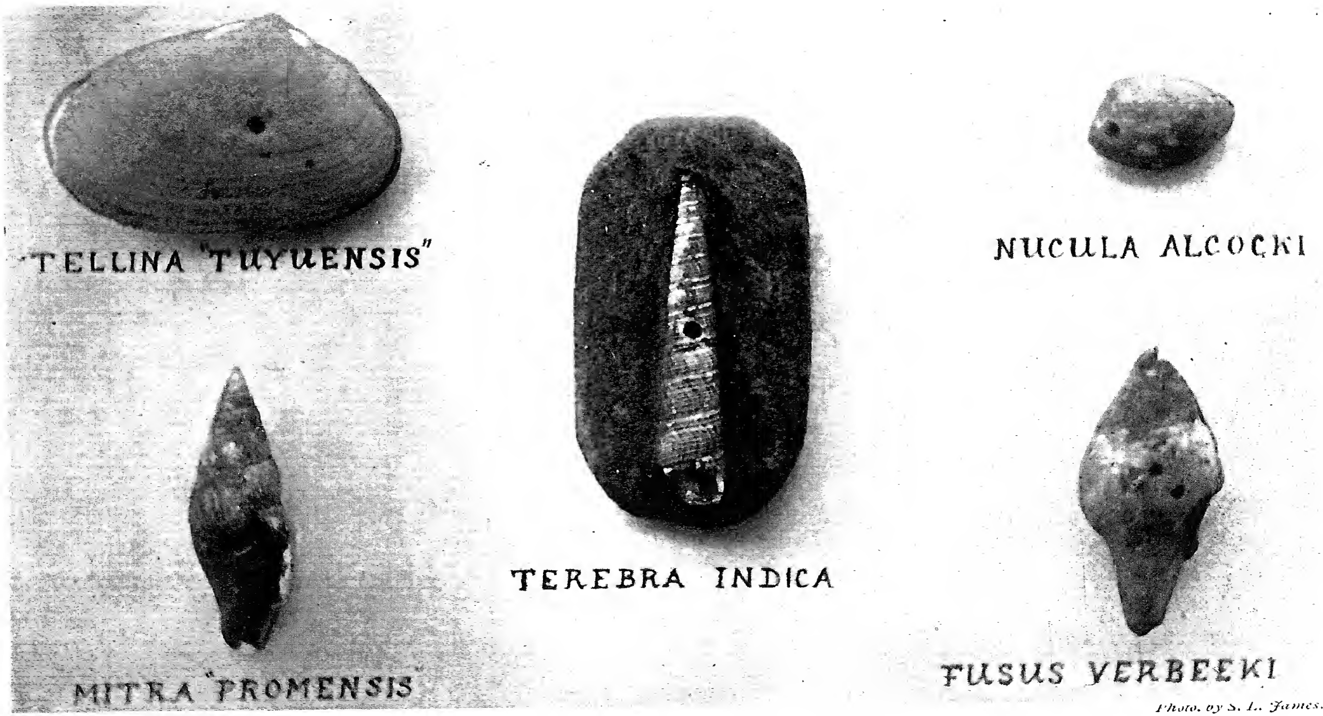

Photo. by S. L. James.

MOLLUSCA FROM THE PEGU SERIES OF BURMA, SHOWING THE DEATH MARK.

nature. The theory, attractive as it may be from the chemist's point of view, fails utterly when applied practically: the artificial light of a laboratory is more favourable to its development than the cold light of facts gathered in the field.

B (2) *Vegetable Origin.*—There remains the theory of formation from vegetable matter. In one form or another this theory has been in existence from a very early date in the history of oilfield discovery and development, and it is held now by many observers who have had to study oilfields, but I am not aware of its having been stated at length in any geological treatise. Consequently the opponents of the theory not uncommonly seem to labour under a totally wrong impression as to what the vegetable-origin theory is, and it has even been stated that distillation from coal or lignite is relied upon by the vegetable-origin theorists to account for the presence of petroleum, an idea to which no practical geologist at the present day would attach any importance.

Perhaps, therefore, it will be as well to state briefly what is the vegetable-origin theory as understood and followed by the scientific prospector or field geologist, before proceeding to give a review of the mass of evidence which leads inevitably up to it.

Petroleum is formed from the remains of terrestrial vegetation, accumulated in clays, sands, or actual beds (which under other conditions would develop into carbonaceous shales, sandstones, and seams of coal or lignite), by natural processes which can be not only reproduced in the laboratory, but can also be proved to have taken place in the past and are taking place at the present day.

In weighing this theory, as in the case of the animal-origin theory, there are first of all some general considerations to be dealt with to ascertain whether there be any inherent improbability in the hypothesis as stated. For the present the actual processes by which petroleum can be formed, or is formed, need not be considered.

The first question to be asked is, "Can sufficient material be accumulated?" In other words, is it possible for terrestrial vegetable remains to be distributed throughout sedimentary strata, or to be formed into beds which can afterwards be entombed to play their part in the geological record? To this question every coalfield or lignite-field, every carbonaceous

shale or sandstone, every peatbog or buried forest, returns an emphatic affirmative.

The second question follows naturally: is it possible from accumulations of vegetable matter to form bituminous compounds or hydrocarbons by natural processes? The coalfields again furnish us with a very definite answer. In nearly every coalfield of importance, and especially be it noted where deep coals in little disturbed strata are worked, there is a considerable proportion of bitumen in one or more seams. Where the coal measures are most disturbed and the seams crop out, the least traces of bitumen are found. Where the coals are most completely sealed up by impervious shale beds, where they are buried deeply or do not crop out at the surface, the proportions of bitumen and gaseous hydrocarbons are, *ceteris paribus*, greater.

To this it may be objected that we are now dealing with oil and not with coal, and that coal and oil are not, as a rule, found in intimate association. This point will be dealt with later; for the present the possibilities alone are under consideration.

There is, then, no difficulty about the accumulation of sufficient material, and material of a suitable kind.

The next point to be considered is under what conditions have the strata associated with coal or lignite seams or carbonaceous shales and sandstones been deposited and consolidated, and under what conditions the strata associated with petroleum. This is a matter that is not always obvious except to the practical geologist. It used to be objected to the "growth-in-situ" theory of coal formation that the fauna of the coal measures is largely marine, but when stated more correctly this objection is seen to have little weight. It should be read as follows: In the coal measures, among the constant alternations of thin beds of shales, sandstones, coalseams, etc., occur here and there beds containing a marine (usually a littoral pelecypod) fauna, while the other strata are mostly unfossiliferous except for the occurrence of terrestrial organisms. These marine beds are frequently mere shell-banks of sandstone, calcareous sandstone, or even limestone or ironstone (*e.g.* "blackband"); they are thin, and liable to rapid lateral variations, as miners of the blackband seams can testify. Speaking generally, our Carboniferous coal measures, or, indeed, any

coal or lignite measures in any part of the world, consist of rapid alternations of thin beds of rapidly accumulated sediment, varied with occasional bands truly marine in origin, and horizons denoting terrestrial conditions. To the geologist such evidence spells littoral, estuarine, or deltaic conditions on a large scale.

But following our method of interpreting past conditions by what we can actually see in operation at present, let us consider in what parts of the world great accumulations of vegetable matter are being formed, where by a slight change of level marine conditions may be brought into play over wide areas, and so marine strata made to alternate with terrestrial. The only places where such an environment obtains on a large scale are in the deltas of great rivers such as the Amazon, Orinoco, Mississippi, Ganges, and Brahmapootra, Irrawaddy, etc., and in neighbouring areas where the same phenomena on a smaller scale may be studied with a greater facility. Within the mazes of a great delta, what are known in South America and the West Indies as "lagoons," *i.e.* swamp-forests growing at sea-level, separated from the sea only by a fringe of sandbanks or a belt of mangrove swamp, cover vast areas. In these swamps and lagoons the accumulation of vegetable matter is remarkably rapid, while in times of flood much of the land is under water, and any slight movement of depression would cause a great advance of the sea-margin and cause marine strata, littoral sands, and fine silts and clays to be deposited over the beds of terrestrial origin.

In the much-written-about, but little known, Island of Trinidad, there is an ideal area to study such conditions at the present day—mangrove swamps, forest lagoons, delta formation, and retreat and advance of the sea under differential earth-movements of very recent date. At sea level can be seen in process of formation terrestrial deposits separated by a strip of littoral sands from truly marine silts and clays, with occasional coral banks in reef formation which will eventually form limestones. Furthermore, a study of the excellent coast sections in that island makes it clear that precisely the same conditions existed throughout the Tertiary period. The same rapid alternations in sedimentary types are seen, lignite seams and oyster beds, littoral sandstones and marine silts, thin calcareous bands and ironstones, in fact all the phenomena of the Carboniferous

Coal Measures may be studied in Miocene and Pliocene strata under the simplest conditions. The higher Tertiary strata on the eastern and southern and western coasts of Trinidad, where excellent and almost continuous cliff sections can be studied and mapped, afford perhaps the finest examples in the world of deltaic conditions on the margin of a Tertiary continent.

One very instructive section in the Sangre Grande Ward may be instanced here. An abundant, though not very rich, fauna of fresh or brackish water mollusca occurs in a grey littoral sand, which also contains the remains of twigs and leaves. On the one side this sand bed passes gradually into fine sands and silts undoubtedly marine in origin, and on the other side into carbonaceous shales with strings and thin beds of lignite. The fossils are undisturbed as they lived, the lamellibranchs having both valves joined and closed. It is quite evident that we have here the sand bank at the mouth of a lagoon, littoral and marine conditions on the one hand, and freshwater or terrestrial conditions on the other. The whole section is not more than 200 yards in extent, and as the beds lie almost horizontally there can be no mistake as to these different conditions existing at the same horizon.

Evidence such as this leaves no room for doubt as to the manner in which these Tertiary lignites and their associated strata have accumulated. Occasionally the evidence is so complete that the course of a Tertiary river near its mouth can actually be traced through the strata, the lagoons on both sides of it roughly demarcated, and the sand and pebble banks that intervened between lagoons and sea mapped. It is even possible by a study of the effects of current action in the sand banks to determine that the prevailing wind was, as it is now, from the east, and by a study of the finer sediments to prove that the climate was wet, the lagoons liable to fresh water floods, and, in fact, that conditions were very much the same as at present.

Now let us turn to the evidence from oilfields to ascertain under what conditions the strata associated or impregnated with petroleum have been formed. So far as lithological evidence goes, the strata of many Tertiary oilfields are exactly the same as those associated with coals or lignites; there are the same rapid alternations, the same constantly repeated minor succession of clay ("underclay" in the case of coal or

lignite) followed by sands sometimes conglomeratic, passing upwards into marine silts and clays, "underclay" again, and so on.

Considered in detail the resemblance is as striking. It is in the thick littoral sands, which overlie the lignite seams, that shell banks occur, and not infrequently ironstone nodules and concretions, suggesting that a concentration of iron compounds under current action may have taken place. Bands of calcareous sandstone, the "hard shells" of the driller's logs, occur not infrequently in these sand groups, and especially at the top of them. These represent littoral deposits in which there was sufficient shell sand to form a cement for the whole bed; when the calcareous material is insufficient for this purpose it occurs in round or disc-shaped concretions often of large size and distributed in more or less regular lines. All these phenomena are as characteristic of the carbonaceous as of the petroliferous phases.

In fact, the only difference is that in the one case we have abundant evidence of vegetable remains in underclays, leaf beds, carbonaceous shales and sandstones, fossil tree-trunks, and seams of lignite or coal, while in the oilfield phase not a trace of vegetable matter is observed, but the porous beds are more or less impregnated with oil or bitumen, which may often be seen exuding at the outcrops.

The next point to be noted is that careful stratigraphical mapping has proved that the same horizons that are carbonaceous in one locality are petroliferous in another, often within quite a short distance; the only variation being that bands of impervious clay are sometimes more conspicuous among, and especially above, the petroliferous strata than among or above the carbonaceous.

This point has been established over very wide areas in Burma, Trinidad, and other countries, by careful geological mapping on the scale of six or more inches to the mile, and the change from the petroliferous to the carbonaceous phase can in some cases be shown to take place within three hundred yards.

First of all, taking evidence on a large scale, Burma furnishes an excellent field for study. The stratigraphical and palæontological work of the Geological Staff of the Burma Oil Co. has proved that the great productions of oil in the

Yenangyoung, Yenankyat and Singu Fields are all obtained from horizons which are represented by the Yaw Sandstone Group and the strata immediately overlying it, which have been mapped and examined over very many miles of their outcrops in the foothills of the Arakan Yomas to the west. These great arenaceous groups exhibit on their outcrops both the petroliferous and carbonaceous phases, the latter however predominating, and the remains of terrestrial vegetation are very common throughout. Traced eastwards these groups are found to become more or less split up by bands of clay and their total thickness perceptibly diminishes, while the petroliferous phase replaces the carbonaceous.

Similarly in other countries where oil and coal or lignite occur within the same series, the same phenomena are to be observed, and it is possible to work out generally the provinces of oil-belt and coal-belt in strata of the same horizon. The Ghasij Shales in Baluchistan afford a striking example; a bituminous coal is worked in one district, while another is characterized by oil-shows derived from the same strata.

To follow this enquiry in greater detail, particular beds may be selected and mapped till the actual transition between the two phases is observed. In Burma, in several localities, lignite beds have been traced into oil-bearing rocks containing no trace of vegetable remains. In the Yaw valley, about fifteen miles south-west of Pauk, is one of the best instances, the lignitic phase being completely superseded and replaced by the petroliferous within a distance of three hundred yards, the outcrop being followed easily as the strata dip steeply, and a hard sandstone bed enables the horizon to be followed without the possibility of mistake. In this case the oil is a light one with a paraffin base and containing a high percentage of solid paraffin.

In Trinidad similar detailed evidence as to the equivalence of lignite seams and oils of asphaltic base is not far to seek. In mapping the southern coast section in that island the author came on a series of lignites and lignitic shales intercalated with sandstones near Grande Riviere. The dip of the strata is vertical, and the strike coincides generally with the coastline which consists of an almost continuous cliff, so that the following of horizons was a matter of the greatest simplicity. Within a mile to the westward the lignitic phase was replaced

by the petroliferous phase in the same horizons, the overlying strata becoming at the same time slightly more argillaceous on the whole through the thickening of intercalated bands of clay. All traces of vegetable remains were lost before the Rio Blanco was reached, and seepages of oil out of the porous beds were observed in several places. This point is important as it has been frequently urged as an argument against the vegetable-origin theory that traces of vegetable organisms are not found among oil-bearing strata. From this section on the southern coast the name Rio Blanco Oilbearing Group was given to the strata at this horizon in the Tertiary series, an horizon which has been proved to be not only petroliferous, but very richly productive in many parts of the island. In only two other localities, and these widely separated, are lignitic strata known to occur at this horizon. It is noticeable that where the petroliferous phase is in evidence impervious clays of greater or less thickness directly overlie, or are observed at no great distance above, the oil-bearing sands.

Still more remarkable evidence is furnished by the so-called "porcellanites" of the western and southern districts in Trinidad. These are naturally burnt shales which have become ignited spontaneously, just as the bituminous Kimeridge clay in coast-sections in the south of England has done on many occasions. The brick-red burnt outcrops of these porcellanites make very striking features in the scenery of the Wards of Oropuche and Cedros, a thickness of as much as thirty feet of strata exposed in a cliff being sometimes burnt and indurated.

When examined closely many of these porcellanites are found to be leaf beds, being a mass of beautifully-preserved leaf impressions; the leaves are those of ordinary terrestrial vegetation, similar, if not actually belonging, to the same flora that flourishes at the present day in the colony. Veins and strings of clinker are seen ramifying through the masses of burnt shale, and occasionally some remains of sticky asphalt may be observed lining joints in indurated but not oxidised portions of the outcrop.

In several cases lignitic seams are observed not far below an outcrop of porcellanite, and Messrs. Wall & Sawkins in their Memoir upon the Geology of Trinidad state that the combustion of lignite has burnt the overlying shales. The author, however, has found no evidence for this; he has never observed

a naturally burnt lignite. It is the shales themselves, either bituminous or in a transition stage between bituminous and carbonaceous, that have ignited spontaneously and burnt. The ignition is probably due to the heat engendered by the oxidation of sulphides, as in the case of the Kimeridge clay; every stream draining a porcellanite outcrop is beautifully clear, and the cause of this is soon ascertained when the water is tasted. It is full of alum, proving the oxidation of sulphides.

One very important point in connection with these porcellanites remains to be mentioned. Their dip is always very gentle, and though the outcrops may be traced for miles along the coast or through the forest, no case of a steeply dipping porcellanite has been observed.

The relation of porcellanites to oil-bearing strata is interesting and carries us a step further in the enquiry as to the cause of the phenomenon. The lower part of the cover-clay of the La Brea Oil-bearing Group is burnt to a typical porcellanite for a distance of nearly two miles along its outcrop. In this case leaf impressions are absent or very rare. Some patches along the outcrop may be seen occasionally smouldering at the present day; Professor Cadman has photographed a smouldering outcrop near La Brea (Plate III). Other occurrences of the burning of the clay above an outcropping oilsand may be seen in the forest south of Siparia and in Burnt Cliff in Barbados, where a petroliferous shale has been burnt along the outcrop for a considerable distance.

This establishes the fact that these porcellanites are as much associated with the petroliferous phase as with the carbonaceous. It might be suggested, indeed, that porcellanite is more characteristic of a petroliferous than of a lignitic series, were it not that leaf-beds are essentially phenomena of the carbonaceous phase; while the occurrence of porcellanites in a lignitic series, where no signs of petroleum have been detected, is very frequent, *e.g.* on the southern coast of Trinidad near Chatham and in the eastern Lignite District near Sangre Grande. In both these localities thick beds of the porcellanite have been traced for miles where no oilsand is known to occur, but where lignites are common.

One coast section west of Irois is specially significant (Fig. 1). A porcellanite outcrop is seen dipping at an angle of some three or four degrees at right angles to the coast line,

Photo. by Prof. J. Cadman.

i. SMOULDERING OUTCROP NEAR LA BREA, TRINIDAD.

Photo. by Prof. J. Cadman.

ii. MUD-VOLCANO IN ERUPTION, TRINIDAD.

and covered by argillaceous beds. This dip brings the outcrop below tide mark where the strata become horizontal. At a distance of less than one hundred yards the strata emerge with a low dip in the opposite direction, thus forming a very gentle local syncline. Where the strata emerge the argillaceous beds have thinned out or become replaced by arenaceous strata, and the beds beneath are no longer burnt but consist of

Fig. 1.—Coast section west of Irois (Trinidad). (Length about 200 yds.)
1. Porcellanite; 2. Clay; 3. Impure lignite and shale; 4. Sandstone.

carbonaceous shales with one seam of impure lignite. This section can be observed from the local gulf steamer on its daily route from San Fernando to Cedros and back, and can be studied in detail during a walk along the beach. The whole section is some two hundred yards in length, and is so well exposed that there is no possibility of misunderstanding.

Such evidence places beyond doubt the connection between the lignitic and petroliferous phases of these Tertiary strata, and emphasises once again the point that a slight difference in environment, the change from an arenaceous, that is to say, a porous, cover to an argillaceous or impervious cover, seems to determine whether the strata have ignited and burnt to porcellanites or have remained as unburnt lignitic shales. It is obvious that where strata lie at low angles the presence of an impervious cover will tend to preserve any combustible or volatile matter that may be in evidence in the underlying strata from being rapidly dissipated or removed by weathering, and thus will favour a slow combustion if a temperature sufficient to cause ignition be reached.

We may safely conclude, then, that these "porcellanites" of Trinidad represent a transition stage between the purely petroliferous and the purely carbonaceous phases, they have been more or less bituminous shales, and to attribute their combustible matter to an animal origin would be the most unjustifiable of assumptions.

The above evidence, selected from a mass of similar details,

is sufficient to prove that *in known oilfields* the equivalence of lignitic and petroliferous beds under slightly varying conditions is indisputable. It remains now to show that *in known coal-fields*, the association of petroleum with carbonaceous strata is, though perhaps rare, by no means unprecedented. The point to be considered is the environment, the conditions to which the vegetable matter has been subjected. There are very many instances on record of a series being petroliferous in the lower beds, and lignitic or coal-bearing in the upper members. In such cases it will always be found that a greater or less thickness of comparatively impervious strata intervenes between the two phases. The section at Point Ligoure on the Western coast of Trinidad shows this very clearly, while in Borneo, Russia, West Virginia, and many other countries, lignite or coal characterizes the less loaded or less perfectly sealed horizons of a series. In the latter country oilwells are sometimes drilled through workable coal-seams, and the bores have to be cased carefully to prevent water entering the coal-seams and flooding the coal workings.

The evidence as to environment is confirmed by recent researches on the nature of coals, and the conditions under which they are found. It was until recently the accepted view that anthracites are characteristic of the most disturbed, contorted, and faulted parts of a coalfield, and that bituminous coals are characteristic of the less disturbed portions. This theory, though there seemed at one time to be ample evidence for it, can no longer be held owing to the careful researches of H.M. Geological Survey in the South Wales and Staffordshire coalfields. Anthracites occur in comparatively slightly disturbed strata in South Wales, and bituminous coal at the same horizons in less disturbed areas. It has been suggested that differences in the original conditions of deposition may account for this, particularly as the amount of ash—inorganic material included in the coal—varies at the same time, being greater in the bituminous coals. Probably a truer explanation is to be sought for in the fact that the anthracites occur where the coal has been open to the influence of deep-seated weathering, and where the structure and nature of the covering have favoured the loss of volatile constituents. The greater original purity of the deposit is also a factor to be reckoned with; a pure coal will readily give up its volatile or bituminous contents, while

an impure coal, owing to the "adsorptive" capacity of finely divided inorganic matter for bitumen, retains it to a much greater extent and will not part with it altogether, even under the action of organic solvents.

Thus it is in deep mines where the seams do not crop out at the surface, but are well sealed up beneath impervious strata, no matter how contorted, that we must look for evidence of petroleum. And the evidence, though somewhat scanty at present, and unfortunately not always recorded, is not wanting. Miners who have worked in deep workings of bituminous coal tell of "tarry oozings" from the neighbourhood of seams, or along joints in hard close-grained strata. Quite recently a seepage of petroleum has been recorded from the Sovereign Pit of the Wigan Coal and Iron Co., at Leigh, Lancashire, at a depth of some 600 yards.

The oil-shales of Scotland, though not oilrocks in the strict sense, add their quota to the mass of evidence connecting petroleum and coal. These shales are contemporaneous with coal-bearing strata, and though they have never, perhaps, been actually petroliferous, they by their nature have been enabled to retain in great quantity the material which under different conditions would have been vast stores of liquid hydrocarbons. The association of coal seams and oil-shale beds is so frequent, *e.g.* in the Wolgan Valley in Australia, that it is unnecessary to enlarge upon this point.

Thus we see that though coal and lignite are very different substances from liquid petroleum, they are inextricably connected; coalfields give evidence of oil and oilfields of coal, transitional stages can be searched for and found, and both asphaltic and paraffin oils are seen impregnating the same strata which at no great distance are carbonaceous in character. Such evidence, almost always forthcoming as the result of careful and detailed stratigraphical work in any part of the world where petroleum is to be found, makes it hardly possible to doubt that it is to terrestrial vegetation that we must look for the raw material from which our supplies of petroleum are derived.

But while stating this conclusion it must be borne in mind that in certain cases, as for instance gas coals and oil-shales, it is quite probable that such animal matter as may have been preserved has borne its, very minor, part. The ammonia

derivable from a gas coal or some of the oil-shales would certainly suggest that some animal matter may have been present. But all oil-shales do not contain ammonia in combination, and petroleum is almost entirely free from nitrogenous compounds, so that we may regard the ammonia contents rather as adventitious than as essential. The Kimeridge clay would certainly be mined as an oil-shale and distilled, were it not for the absence of ammonia, which, fixed as the sulphate, is the most valuable by-product of the Scottish oil-shales.

B. (2) *Vegetable Origin.*—Before leaving this branch of the subject, it is necessary to refer to an idea or hypothesis frequently put forward in a rather indefinite manner, but which has found favour with many, especially those who have little field experience.

This hypothesis is that petroleum is formed from marine vegetation; in other words seaweeds or fucoids. It was apparently the desire to find some marine origin for oil that caused this theory to be taken up, and allusions to "fucoids" by writers on the subject of petroleum were at one time very frequent.

But the origin of the theory was a series of observations made on decomposing seaweed on the coasts of Sicily, Sardinia, Norway, and other countries, where a "jelly-like substance" was found to be formed at one stage of the subaerial decomposition. This "jelly-like" matter was somewhat loosely described as "substances resembling petroleum," and the theory of a seaweed origin for oil sprang to birth in the minds, not of the observers themselves, but of others who read about it. The theory was again revived by the discovery of "Nhangellite" formed in Portuguese South Africa, by the decomposition of fresh water algæ in dried-up shallow lakes, and the claim that this Nhangellite was evidence of the existence of petroleum in the neighbourhood. In 1906 the author was asked to investigate this claim in the field, but the evidence seemed insufficient to justify the necessary expenditure of time.

So far as geological field evidence has been adduced in favour of this theory, it has been confined to the production of a few specimens of so-called fucoids, but in most cases, as in the famous case of the Cambrian Fucoid Beds of the north-west of Scotland, examination has proved the so-called "fucoids" to be worm tracks and burrows. The exposure of this evidence,

however, has not entirely removed the theory from currency: a theory can, it appears, survive the loss of the last piece of direct evidence in its favour.

Let us again appeal to the facts and consider what evidence can be brought up for and against a seaweed origin for petroleum. In the first place, are there any inherent improbabilities in the theory? Is it possible for seaweed to be accumulated in vast quantities and entombed in sediments as they are deposited? That vast quantities would be required will be admitted, as by far the greater part by weight of seaweed, about seven-eighths, is water.

Under what conditions do seaweeds flourish most luxuriantly? It is a simple matter of observation. On rocky coasts, in comparatively clear water, and in stagnant marine areas such as the Sargasso Sea, seaweed can grow abundantly. But in neither case is there any probability of the seaweed sinking and becoming entombed in sediment. On rocky coasts the weed is torn off by storms and cast on the shore, *e.g.* in the west of Scotland and Ireland, where kelp-gathering is a regular industry. In the Sargasso Sea the weed is floating or attached to floating timbers, the remains of derelicts, etc.

In deep water, beyond the laminarian zone, seaweeds are rare, small, and insignificant. In muddy estuaries, under deltaic conditions, which have been proved to be the environment in which strata now oil-bearing have accumulated, where in fact sedimentation proceeds apace, there would seem to be some possibility of weeds becoming involved and preserved in the rapidly forming deposits, but in such conditions the waters are singularly free from seaweed growth. Thus the initial difficulty of postulating the possibility of a sufficient quantity of raw material is, perhaps, even greater in the case of the marine-vegetation theory than in the case of the animal-origin theory.

Turning to chemical evidence, there are facts even more difficult to explain away. When the water is removed from seaweed, of the remaining solids a considerable proportion is bromine and iodine in the form of salts. In fact, it is from the ash of seaweeds that these elements are extracted commercially. If petroleum is formed from the remains of seaweed, what becomes of these bromides and iodides which must be present in enormous quantity? In one case a trace of iodine has been

detected in the water from a mud-volcano, but the proportion was quite insignificant compared with the trace of petroleum in the same water.

The marine-vegetation theorists must account for the loss or disappearance of these salts before they can justify the chemical possibility of their hypothesis. Again, practically every sample of petroleum that has ever been analysed contains some trace of sulphur, and the percentage rises to three or more in some cases. But there is no sulphur in seaweeds.

The chemical difficulties to be surmounted are therefore as insurmountable as the initial difficulty of accumulation in sufficient quantity.

If field evidence of unimpeachable character were available, the matter would be worthy of serious consideration; if fucoids and traces of fucoids were found in quantity throughout a series, and only disappeared among strata actually petroliferous, it would be necessary to give special attention to the role played by that class of organism and the strata in which the evidence occurs, but when most, if not all, of the so-called "fucoids" are worm-casts and tracks of animal organisms, the practical geologist is unable to treat the theory with respect.

Thus every hypothesis but that of the origin from terrestrial vegetation fails when tested by an appeal to the facts to be observed at the present day, and we may confidently state that the only source of origin which is at the same time adequate and within the bounds of chemical and physical possibility is terrestrial vegetation.

CHAPTER II

PROCESSES OF FORMATION

In the last chapter we have dealt with the material from which petroleum is, or can be, formed, and the various theories that have been put forward to account for its origin.

It now becomes expedient to consider the processes through which the raw material must pass in order to convert it into the mixture of saturated and unsaturated hydrocarbons which we know as "crude petroleum." The problem is to find out what these processes are, and how they have affected the raw material.

A simple distillation caused by heat will not meet the case entirely. We have seen already that such distillations take place in nature where igneous rocks invade coal or oil-shale measures. Instances of this are frequent among the Scottish oil-shales, and semi-liquid bitumen occurs as an impregnation in porous strata or along joints and in cavities for some distance from the shale bed or from the intrusion. But the result is not the reproduction of an oilfield on a small scale, nor could the process take place upon a sufficiently large scale.

What is required is a simple, slow, natural process which can take place over wide areas. It is, without doubt, more in the province of the chemist than of the geologist to make investigations with the view of determining under what conditions in nature it is possible to form petroleum from whatever raw material is available; but the geologist's evidence is necessary, if only to prevent undue attention being given to entirely artificial conditions which may be arranged for in the laboratory, but which can hardly be reproduced in nature.

Many chemists have conducted researches upon petroleum with a view to proving its mode of origin and the processes necessary for its formation, and no more careful and interesting work has been done than by Engler and Hofer. These observers

state very clearly the conditions under which the reactions they observed and controlled took place, and the care and accuracy of their researches cannot be doubted. But they do not—and the same objection applies to the work of many others on the same subject—approach the inquiry from the point of view as to what conditions are possible in nature, conditions which the geologist in however rough a manner is able to define. Thus the work of these scientists, careful and painstaking as it is, is open to the charge of what might be called a form of special pleading in experimental work. Given the conditions they postulate, the results are certain, but if such conditions are practically impossible on a large scale in nature, the researches conducted in a laboratory become of little value to the practical man whose business is to find oil.

The geologist from his observation of the conditions under which petroleum occurs, knows the conditions to which the series of strata containing petroleum must have been subjected. Some universal process, subject to these conditions, is called for, and it is the duty of the chemist rather than of the geologist to reproduce as far as is possible the conditions so defined, and to prove whether it is possible to form the mixture of hydrocarbons known as crude petroleum from the raw material supplied and under the stipulated conditions.

Now the only conditions which the geologist has any right to dogmatise about are depth-temperature, pressure, the presence or absence of water, the nature of the raw material, and the question as to whether or not the strata in which the chemical reactions take place have been sealed and isolated from the introduction of extraneous material.

In the last chapter the nature of the raw material has been discussed at length, and, so far as is possible at present, determined. The calculation of depth-temperature is simple, and within reasonable limits the temperature at which oil may be formed can be deduced from incontrovertible evidence. The calculation of pressure is a matter of much greater difficulty, and there must necessarily be a very wide range between the minimum and maximum pressures postulated. The sealing up of the strata, in other words the determination as to whether the reactions have taken place in open or closed retort, is again a matter of easy determination, seeing that it is admitted by all observers that for the formation or preservation of oil impervious

strata must overlie the petroliferous rocks. Similarly the presence or absence of water, argillaceous material, sodium chloride, and other material either active or inert in the chemical sense, can be deduced with a fair degree of certainty.

Here we must turn to the laboratory to learn what experimental investigations will come to our aid; it is a question of conditions favourable to chemical reaction.

It has been stated that wood sealed in a closed tube with a small quantity of water and subjected to great pressure at ordinary temperatures has produced a small quantity of mixed hydrocarbons analogous to a crude petroleum, but I have been unable to verify this interesting result or to obtain any details about the experiment. The various attempts, however, to make commercial use of peat-masses furnish us with valuable evidence. In Ireland, Sweden, the United States, and other countries, the problem of how to utilize the enormous accumulations of peat has for many years occupied the attention of practical chemists and chemical engineers, and after many failures it seems that some of the processes are within sight of commercial success. Without disclosing information confidentially received it may be stated that all these processes have this in common, that the peat after being dried and perhaps ground and again pressed into briquettes, is subjected to destructive distillation in the presence of a *limited quantity* of water, under great pressure, and at a comparatively low temperature.

The resulting products are various according to the end aimed at and the different pressures and temperatures in each case. Bituminous compounds, petroleum of almost every grade, and even coke may be obtained, while ammonium salts may be recovered as sulphate by a process similar to that used in the oil-shale and gas industries.

The important points for the geologist to note are that petroleum of various grades and in great quantity can be produced, and that the essential conditions are great pressure, comparatively low temperature, and the presence of a limited quantity of water.

Water is in any case present in the peat, even after drying, for it is as impossible, without destructive distillation, to remove the combined water in peat as it is in the case of a lignite.

It is obvious that similar conditions can easily be obtained

in nature. The presence of water in greater or less quantity is almost inevitable in sedimentary rocks, the requisite pressure is amply provided for by a covering of a few hundred, or it may be thousand, feet of superincumbent strata, while as soon as decomposition commences the potential gas pressure may become so great that almost any hydrostatic pressure required can be obtained. The temperature, increasing as it does on a general average one degree Fahrenheit for every 55 feet of descent into the earth's crust after the first hundred, would soon be raised sufficiently to favour chemical reaction, while as pressure increased the temperature would also rise till the necessary equilibrium was reached. Thus once the process of petroleum formation has commenced, its action is probably automatic and must be complete, unless there is a change in conditions. The sealing up of the strata by impervious rocks, so that escape of gaseous or volatile compounds is entirely prevented or rendered so slow and gradual as to be quite insignificant, is, as has already been stated, a question upon which there is a general consensus of opinion.

It seems probable—but here we enter into speculation—that it is the *pressure* that is the determining factor, as it is in so many chemical reactions. Given the vegetable matter from which petroleum can be formed enclosed in a well-sealed deposit, given the presence of a limited quantity of water, and the necessary, but by no means high, temperature, as soon as the pressure reaches a certain point the action will begin. In a deltaic area undergoing earth-movement, as is almost invariably the case on the margin of a continent, sediment accumulates very rapidly. A geosynclinal on a large or small scale, in fact, is formed, and though sedimentation may occasionally outstrip subsidence, or subsidence outstrip sedimentation, the general result is the growth of the deltaic deposits outwards by progressive sedimentation over a continually increasing thickness of strata belonging to the same series. In such circumstances the requisite pressure for the formation of petroleum may easily be obtained in the strata sufficiently deeply buried.

Another probable effect of pressure also must be considered; *ceteris paribus*, the quality of the petroleum formed is likely to depend upon it. In the process of isomerisation of organic compounds, it has been proved over and over again in the laboratory that pressure is usually the determining

factor. Thus a higher pressure may determine a more complete condensation of the volatile compounds and gases into light oils, provided that such condensation is accompanied by a decrease in total volume. The fact that in many oilfields where several separate sands at different depths contain petroleum, the specific gravity of the oil generally decreases as the depth increases may not be due in all cases, as has often been assumed, entirely to partial and progressive inspissation of the shallow oils, but partly to the pressure under which the petroleum has in each case been formed.

On this hypothesis of oil-formation the importance of an impervious "cover" also becomes apparent. The "cover" is in effect the lid of the retort in which the chemical processes take place. If the lid be imperfect or imperfectly closed, escape of gaseous products must ensue, pressure can never become very high, and the entire process of oil-formation may be prevented, arrested, or permanently stopped. Coals or lignites and carbonaceous shales and sandstones will be the result. This accounts for the occurrence of porcellanite beneath or forming part of a bed of shale or clay, while the lignitic or carbonaceous phase is in evidence where the cover is arenaceous and porous.

It has been suggested, on account of the association of oil-bearing rocks with clays or shales often of great thickness, that the argillaceous strata may have had some actual part in the formation of the petroleum. This is a point very difficult of proof, either for or against, since to bring actual evidence of the favouring of chemical action by the presence of argillaceous material which itself remains unaffected is well-nigh impossible. It is quite probable that much of the material from which petroleum is formed has been deposited with and included in argillaceous sediment, witness the leaf beds which have been burnt at outcrop to porcellanites. It is also certain, as proved by Mr. Clifford Richardson, that clays can absorb and "adsorb" bitumen to a remarkable extent, and can be used to filter solutions of asphalt and asphaltic oils. But these facts are not proofs of the argillaceous material taking any actual part in the chemical processes by which oil is formed, even as what used to be called a "carrier," a compound which, though itself apparently unaltered, enables chemical action to take place by continual decomposition and simultaneous re-formation. It is

an interesting field for research for chemists to enquire into the possibility of argillaceous strata having some such essential role to play. For the geologist the matter of importance is simply that potential oil-bearing strata require an impervious cover if the oil is to be formed, and, when formed, if it is to be preserved from inspissation, and that argillaceous rocks, especially fine marine and estuarine clays and shales are the best and most usual "cover-rocks."

By studying the subject of pressures in the earth's crust, and by careful measurement of sections where oil-bearing strata are exposed, it may be possible to arrive at some idea of the pressure necessary for the formation of petroleum. In many cases where large thicknesses of strata are exposed it will be found that the lower part of the series is petroliferous and the upper part carbonaceous, without there being any essential change in the character of the intercalated sediments associated with the oil-bearing and lignitic bands. It may be that the upper part of the series has never been under sufficient pressure to bring about petroleum-forming reactions.

Let us take a specific case and attempt, however roughly, to calculate the maximum and minimum pressures which can have been exerted during the formation of the petroleum. At Point Ligoure on the western coast of Trinidad, where the Guapo Oil Company is operating, there is a very clear section exposing some 1300 feet of strata, the dip varying from vertical at the northern and lower end of the section to 56 degrees at the southern and upper end. The lower 600 feet are in the petroliferous phase, and several bands of oil-rock are exposed especially near the base of the section. In the upper 200 feet of the section lignitic clays and sands with underclays and thin seams of lignite are observed. In the lower part of the section the strata are somewhat more highly mineralized, concretions chiefly cemented with iron-salts are more frequent, and there are several beds of fairly stiff argillaceous material intercalated with the oil-bearing sandstones and above them. In this case the mapping of the neighbouring districts has proved that probably not more than 800 to 900 feet of strata have ever been deposited above the uppermost beds in the measured section. Assuming that such a total thickness of beds has been deposited in a horizontal position, and again, assuming that the pressure can be calculated as a hydrostatic pressure

directly due to the weight of the superincumbent strata—these being great, and perhaps hardly justifiable assumptions—it is possible to calculate the pressure to which the strata containing the raw material from which petroleum can be produced have been subject.

Taking the specific gravity of the strata to be on an average 2·7, we arrive at the result that the maximum pressure exerted and applied in this instance has been 189 atmospheres, or some one-and-a-quarter tons per square inch, and the minimum approximately 135 atmospheres or rather less than a ton per square inch on the strata now found to be oil-bearing, while a pressure of 99 atmospheres was apparently insufficient to determine the formation of petroleum. This calculation is, of course, open to many sources of error, and it is improbable that such high pressures have been exerted in this case, as earth-movement and denudation probably prevented the accumulation of any such thickness of strata in a horizontal position. The figures are only given to suggest a form of enquiry in which the observation of facts in the field may enable the geologist to obtain evidence as to the conditions requisite for the formation of petroleum. In this case the oil, as yielded at present, is of fairly high gravity with an asphaltic base. Another instance may be cited from a different region. In the valley of the Yaw, in Upper Burma, an excellent section through the entire Pegu Series of Burma may be studied, the total thickness being some 8000 feet. The lower 3000 feet exhibit here and there evidence of the petroliferous phase in seepages of a fairly light oil with paraffin base, but lignitic beds begin to appear on the same horizons as the oil-bearing rocks at about 3000 feet above the base of the series. Then, after passing upwards through some 1300 to 1400 feet of strata chiefly of solid clays, the lignitic phase is well represented by a series of seams with intervening underclays and sandstones, and up to the top of the section no further evidence of petroleum is forthcoming. In this case it is practically certain that earth-movement had begun long before the deposition of the higher beds, and that the strata were never superimposed upon each other in a horizontal position. Thus calculations of pressure and temperature from the data as given might be entirely erroneous. The points to be noted, however, are that a transition from the petroliferous to the carbonaceous phases takes place at a fairly

definite horizon in the series, and that this change may not be due entirely to the sealing up of the strata in which petroleum is now found, but to a direct effect of different pressures.

Numerous other instances could be given, but these are sufficient to suggest a field of enquiry which might be followed up by laboratory experiments, the results of which might throw light upon the conditions governing the formation of mineral oils of every grade and nature.

Temperature.—The evidence as regards the temperatures at which petroleum may be formed in nature is no less interesting. It is evident that if depth-temperature alone is to be considered, and in the case of most oilfields it is impossible to postulate any other phenomenon capable of causing a rise in temperature, there is no very great range of temperature available. In the case of Point Ligoure a rise in temperature of 40 degrees Fahrenheit would be all that could be granted. In the case of the Yaw Valley it would not be safe to calculate upon a rise in temperature of more than 52 degrees or 53 degrees.

Thus we see that the researches upon peat furnish an interesting and attractive suggestion as to the conditions under which mineral oils are formed in nature. High pressure and comparatively low temperature are the conditions under which petroleum can be produced from the vegetable matter of peat masses, and similar conditions are at the least easily obtained in the strata of what are now oilfields. The high temperatures required for the destructive distillation of animal fats to form distillates consisting of a mixture of hydrocarbons similar to natural petroleum, are not only unnecessary, but can hardly be assumed to be within the range of possibility.

Salt and Brine.—One other interesting and even puzzling feature about many oilfields is the frequent association of petroleum with brine or rock-salt.

The first oilwell drilled in America was intended to reach brine and not petroleum, and in many other countries it has been in the search for brine or salt that oil has been found. In very many oilfields, also, the water associated with the petroleum or occurring in porous beds below it, and also frequently above it, is brackish or even highly impregnated with sodium chloride. In mud-volcanoes also, the water and mud discharged are almost invariably saline.

It has been claimed that the occurrence of this brine is confirmatory, in some unexplained manner, of the theory that it is in marine strata and from marine organisms that petroleum has been formed, and the well-known antiseptic properties of common salt, under subaerial conditions, be it noted, have even been adduced as being likely to favour the partial and selective decomposition of animal matters which would be necessary if petroleum is to be formed from them.

Into this speculation the author does not care to venture, for lack of sufficient detailed evidence. But it must be admitted that the terrestrial vegetation theory does not on the face of it explain the presence of these saline waters, nor does their origin from vegetable matter seem possible.

Without attempting an explanation, however, it is possible to review such facts as bear upon the problem and to consider how far these facts may indicate a possible solution.

In the first place it is necessary to ascertain whether brine and petroleum are always associated or not; in other words whether the former is an essential concomitant, or whether its occurrence may or may not be due to causes not in themselves directly necessary to the formation of mineral oil. Unfortunately we are at present unable to answer this question with certainty. In some oilfields a strong brine underlies or accompanies the oil in every petroliferous band, in most cases what water is found is slightly saline or brackish, in a few cases there is little evidence of salinity. In the famous Yenangyoung field of Burma the waters met with in the upper oilsands, or in water-sands between them, are fresh or only moderately brackish, while a distinct brine has been struck in the lowest sand penetrated up to February, 1911. In this case, however, it may be that the upper waters have been briny and have been diluted by the incursion of surface water. Thus the percolation downwards of fresh water may result in the occurrence of a small quantity of brine in the oilrocks being overlooked.

Many oilfields contain regular beds of rock-salt, *e.g.* Luristan, Persia and Texas, and these deposits may be found both above and below oil-bearing strata. Again, in Persia brine springs giving rise to saline rivers rise from some of the strata which are approximately on the same horizon as oil-bearing rocks in neighbouring districts. In the cases where brine is

most conspicuous, a suggestive subject for enquiry is the investigation of the evidence as to the conditions under which the strata now containing brine have been deposited, while it is also necessary to take into account the present climatic conditions under which the strata are observed.

In Persia, in the oilfields of Luristan, and more especially in the strata overlying the known oilrocks, we have almost every possible proof of a former desiccation during formation Red-coated mudstones and sandstones, deposits of gypsum on a gigantic scale, Brockram-like breccias on the flanks of limestone outcrops unconformably overlaid, are the rule throughout a vast thickness of strata. Furthermore there is indisputable evidence of a contemporaneous earth-movement that shut off basins and allowed the desiccation to take place. The occurrence of beds of rock-salt, therefore, can readily be understood, quite apart from any suggestion of its being essentially associated with petroleum. Furthermore, the climate of this region (Plate IV) is very dry, absolutely rainless throughout a great part of the year, so that there is no excess of surface waters to dilute and disguise the presence of brine in the strata. The importance of this point concerning climatic conditions at the present day can be appreciated when the logs of the wells drilled in the Maidan-i-Naphtun field in Persia are studied. Hardly any water has been encountered at any depth in any of the wells. The significance of this point will appear shortly.

In Baluchistan in the Khatan oilfield, a region almost rainless, the waters associated with and accompanying the oil are impregnated with salts, but instead of sodium-chloride it is largely the sulphates of sodium and calcium that are present. These salts occur frequently throughout great belts of the dry zone, and are characteristic generally of arid regions, quite apart from oilfields. Such evidence suggests that there may not be any essential connection between the occurrence of salt or brine and petroleum.

The whole question, however, requires exhaustive research before it can be decided whether or no the oil and brine are due to the same chemical action, whether they are different effects of the same causes, or whether their association is merely adventitious. In the answers to these questions probably lies one of the most illuminating generalizations yet to be made in

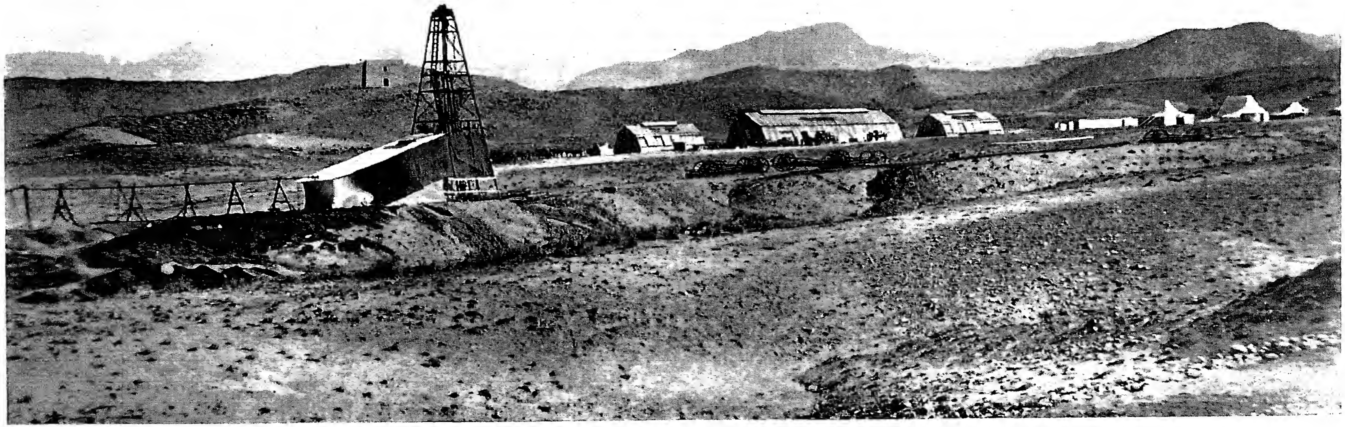

Photo. by G. B. Reynolds.

THE MARMATAIN OIL-FIELD, PERSIA.

Shewing the bare nature of the country.

the geological study of petroleum, and one which may be of great practical value to those who have to exploit new oilfields.

What is required is a large number of analyses of the brines and brackish waters found accompanying or underlying the petroleum in an oilrock or discharged from a mud-volcano. In each case it must be known from what depth the water was obtained, with what particular kind of oil it was associated, paraffin or asphaltic, high or low grade, whether sulphur compounds were present in the oil, and if so, in what percentage, and whether there has been any possibility of surface waters having percolated downwards and mingled with the brine or brackish water. Without precise data of this kind it is dangerous to generalize.

The only suggestion that the author would put forward is that it must not be forgotten that salt and petroleum may be entirely unconnected. Every sedimentary rock—and many igneous rocks for that matter—contains either sodium chloride or ingredients which could furnish that salt if the rock were sufficiently lixiviated. Where water is in excess, as in water-bearing strata, the percentage of sodium chloride is so small as to be inappreciable, but where water is in smaller quantity and has percolated through a considerable thickness of strata it is possible that a considerable concentration of saline matter in solution may have taken place. Now we have seen that one of the probable conditions under which petroleum has been formed is the presence of a *limited quantity* of water. Much of the hydrogen also may be utilized in the formation of the mixture of hydrocarbons which we know as crüde petroleum, but this is very doubtful, as it would necessarily involve the oxidation of any oxidizable material in the vicinity. However this may be, it is evident that any residual water might become a fairly concentrated solution of saline matter. As we have seen that petroleum is formed in what we may consider a closed retort, circulation of subterranean waters and percolation of water from upper strata might be impossible or only possible to a very slight extent, and a brine associated with the oil or underlying it might survive without dilution till the oil-bearing strata are pierced by the drill. The evidence of desiccation in the strata overlying petroliferous rocks in many oilfields shows that excess of water is not a probable condition in

the series containing oil, for where rainfall is scanty and evaporation rapid the absorption of water by the strata must be minimised.

This hypothesis as to the reason why saline water is usually found in association with petroleum is only put forward as a suggestion, which must be tested by application to facts as observed; it is merely stated now as a guide to the direction in which future research may prove profitable.

There is one other point in connection with the formation of petroleum which cannot be too clearly insisted upon. It is the common practice to distinguish between oils of asphaltic base and oils of paraffin base, and they are often spoken and written about as if they were entirely different minerals. In some cases it has even been suggested that they have been formed from different raw materials.

But there is actually no hard and fast line between asphaltic and paraffin oil; many asphaltic oils contain a percentage of solid paraffin, and many so-called paraffin oils can be made by careful distillation to yield a residue of asphalt. In fact, there is less difference between different crude petroleums than between different coals, which, as is well known, show every gradation from the least mineralized lignite with a high percentage of water, through bituminous coals and gas-coals to anthracite, and, perhaps, finally even to graphite.

It has been shown that the light paraffin oils of Burma, with percentages of solid paraffin up to as much as thirteen, and the heavy asphaltic oils of Trinidad can both be proved to have been formed from vegetable matter, while the paraffin oils of Trinidad, with percentages of solid paraffin up to six (though they occur under slightly different conditions from those in which the asphaltic oils are found, in the former case impregnating thin oilsands very well sealed up amidst thick masses of clay), give no evidence of an essentially different origin.

To account for the differences in grade and class of crude petroleum, we must look to variations in the conditions of formation; different pressures are probably the most important factors, but differences in temperature, relative quantity of water present, and many other local conditions probably all play their parts. In these questions there is need for much research and experimental work in the laboratory, and it is

hardly within the province of the geologist to speculate upon the effects of the environment to which the raw material was subjected. It is, however, the geologist's task to deduce and discover as far as possible what that environment must have been, so that armed with the knowledge thus gained the chemist's task may be simplified.

CHAPTER III

THE MIGRATION, FILTRATION, AND SUBTERRANEAN STORAGE OF PETROLEUM

It is necessary now to consider what may happen to the crude petroleum after it has been formed, what movements are possible for it, and the reasons for those movements, how it is concentrated and stored, and how it may be affected in grade or quality by the conditions to which it is subjected. The migration, filtration, and storage of oil in nature are subjects so inextricably connected that they can hardly be considered apart; they must all be understood by the geologist if he is to be capable of reading field evidence correctly and assigning its true significance to every indication which he may have to consider of the presence of petroleum, at the surface or in a well.

The causes for the migration of oil are earth-movement, hydrostatic pressure, and gas pressure. There are many factors which determine movements of oil, but directly or indirectly all movements are due to these three causes. The theory that oil is underlain by water or brine and has been floated up by the heavier liquid through porous strata, and thus by the hydrostatic pressure of the water forced towards the crests of flexures or to outcrop, is pretty generally accepted, and certainly in fields such as those of the Eastern States in America, where the strata often lie at low angles over great stretches of country with very small and gentle flexures and disturbances, and the porosity of the rocks does not vary sufficiently to hinder migration, there may have been a great lateral progression of petroleum towards the localities best adapted for storing it. But cases are not always so simple, and to assume that in any oilfield the petroleum contents have originated at a great distance, and have only reached their present position after a wearisome journey, is quite another matter. The insistence

upon the migratory feats of petroleum has arisen to some extent, at least, from the desire to account for the formation of the hydrocarbons from animal matter. Thus, on the theory that the oil of the Californian and Texas-Louisiana fields has been formed from the soft parts of foraminifera preserved in thick masses of shales and clays, it is necessary to postulate a migration of each minute particle through almost impervious strata in a certain direction to form an accumulation in a porous stratum. To attribute such a movement to the hydrostatic pressure of water is perhaps to attach too great importance to an action which in porous and inclined strata does without doubt take place. But it has already been shown on what very doubtful evidence a foraminiferal-origin theory rests. If on the contrary the oil is formed from accumulations of vegetable matter, it is not necessary to postulate extensive migration as a rule; strata capable of containing the petroleum are usually at hand, and in these strata it will be found. The Tertiary Series in Burma and Trinidad, where great thicknesses of strata of estuarine origin are present, supply abundance of evidence on this point, while lignitic or carbonaceous beds contemporaneous with the oil-bearing strata, and at no great distance from them give evidence of the presence of the raw material, and suggest that no great or extensive migration is necessary.

Hydrostatic Pressure.—It is the geological structure and the porosity of the oilrocks that determine the effects of hydrostatic pressure. The rocks must be sufficiently porous to admit of free, if slow, movements of the aqueous contents, and the strata must be sufficiently inclined to determine the direction of movement. Thus towards the crests of anticlines, both laterally and upwards, there must in nearly every case be a gradual migration of oil by the gradual replacement by water in the lower levels, when there is a sufficient difference in the specific gravities of the liquids. In a subsequent chapter the various structures that favour such migration will be dealt with.

The question of specific gravity becomes in some fields a matter of great importance. The fact seems to have been lost sight of occasionally that a heavy asphaltic of say 0·95 specific gravity or higher will be affected much more slowly than a light oil of 0·72 specific gravity. Consequently in considering lateral or upward movements of petroleum the particular

grade of the petroleum must be taken into account. To overcome the friction and the viscosity of the oil which must necessarily retard percolation, a considerable advantage in specific gravity must be possessed by the water. Thus to generalize on the subject of migration of oil from facts ascertained in the Pennsylvania fields, where a light paraffin oil is found, and to apply the generalizations to such fields as those of California, or even Baku, where an asphaltic oil of heavier gravity is the rule, is, to say the least, very unsafe.

Gas Pressure.—Another cause of what may properly be called migration of oil is gas pressure. The gas may not exist as such in the strata, being dissolved and occluded to a great extent in the petroleum, or the pressure may be too great to allow of the existence of gas if it is below the "critical temperature." In that case the gas will be in a potentially gaseous state, and must exert an enormous pressure in seeking to find space in which to expand to the gaseous state. The terrific force with which such gas is disengaged on the striking of a prolific well is sufficient evidence on this point, as it is now admitted that gas pressure is the chief if not the sole cause of fountains or flowing oilwells. This gas, dissolved, occluded in or mechanically associated with the oil must exercise pressure *in all directions*, and here again comes a point that has frequently been lost sight of. It is often assumed that the movements of gas and oil must be directly or indirectly upward, and this has often caused deplorable errors to be made in the location of oilwells and in the deepening of wells long after they have passed through the lowest strata in which there is any hope of oil being struck. A "show" of gas in a well has only too frequently been understood as a sign that oil must lie beneath.

But if gas exerts pressure in all directions it will migrate in all directions till stopped by some impervious stratum. Thus both laterally and downwards there may be a migration of gas carrying with it probably small quantities of the lighter constituents of the oil. The oil will gradually be trapped during the migration, especially by argillaceous strata, so that the gas finally reaches furthest from the parent source. It is owing to this that we find gasfields spreading beyond the confines of an oilfield, and profitable productions of gas may be obtained near a prolific oilfield but in localities where no

oil can be struck and where the strata may be substantially waterlogged. Instances of this are not uncommon in Burma.

Again, gas may be found beneath the oil-bearing strata, and may be evolved from clays and other almost impervious rocks long after the porous oil-bearing strata above have been removed by denudation. The impregnation of strata unconformably overlaid by oil-bearing rocks has been observed in many parts of the world; good instances are recorded from Alaska, where metamorphic rocks have been impregnated from the Tertiaries above them, and from Galicia, where Cretaceous strata contain oil derived from an overlying Tertiary Series. Such cases of impregnation have also come under the writer's personal observation in Baluchistan and Trinidad. In Burma also there is some evidence of deep wells passing through the petroliferous Pegu Series and striking oil in the unconformable series beneath. In some of these cases the strata beneath are argillaceous, so that they contain little more than gas, and perhaps a little filtered oil, the exudation of which when exposed at the surface is naturally very slow.

In the south-eastern corner of Trinidad slow evolutions of gas may be seen from an outcrop of clay of the Cretaceous Series, which is not petroliferous in the district, but which is overlaid unconformably in the immediate vicinity by oil-bearing Tertiary sands. In the Piparo district of the same island the discharge of gas in one locality has been sufficient to form two small mud-volcanoes on an outcrop of Cretaceous clay which was not originally petroliferous. In this instance, however, the volcanoes may be fed from some more porous strata beneath, which have been more completely impregnated from the Tertiaries.

Filtration Effects.—Any oil appearing with the gas in such cases will probably be well filtered and to a large extent decolorized. Professor Clifford Richardson has proved that by continued filtration through clay solutions of asphalt and petroleum of any kind may be almost completely decolorized owing to the absorptive and "adsorptive" properties of the clay. The fraction "adsorbed" cannot be extracted again by treatment with solvents, and so is distinguished from that absorbed. This phenomenon is very suggestive, as similar conditions may easily be reproduced in nature. Where oil is obtained from argillaceous rocks it is almost invariably

light in gravity and colour, and productions are not as a rule large nor gas pressure great. The water-clear oil of Kala-Deribid in Persia (Plate V) is the most striking instance that has come within the writer's observation. This oil, which is perfectly "water-white," collects very slowly in small holes dug in the outcrop of a fine-grained, compact shale, exposed in a small stream valley. There is very little evolution of gas in this case, only a few bubbles being noticed, as compared with the brisk evolution so frequently observed from an outcrop of oilrock. The "show," though on the crest of a large and sharp asymmetrical anticline (Plate VI), is not concentrated towards the actual line of crest, but distributed for some 20 or 30 yards through the outcrop of the shale on the gently dipping flank of the flexure. This surface indication, in fact, differs essentially from the usual show of oil on an anticlinal crest; the petroleum does not seem to be forced up or carried up by gas, but collects particle by particle, just as water collects in an excavation in a water-bearing sand. The greatest yield is about four kerosine tins per day.

Close above the shales occur several outcrops of rather loosely compacted sandstone, which have all the appearance of weathered oilsands, but which, beyond traces of sulphur, contain no sign of oil. Such traces of sulphur are often the last surviving evidence (in a thoroughly lixiviated sand) of the former presence of oil which contained sulphur.

The author's theory with regard to this water-clear oil is that it is a filtered residue yielded slowly by the almost impervious argillaceous rock, that we must look for its origin in oilsands lying above the shale, and that it affords an instance of downward migration of oil, only the filtered remains of which have been preserved by the less easily weathered shale.

Filtered oils, varying in colour from water-clear to that of a well-matured brandy, which are obtained in small but payable quantities from shallow wells in the limestone of Ramri Island off the coast of Arakan, have probably a similar origin. The yield is steady and slow, the gas pressure small, while inspissation has, as in the case of Kala-Deribid, removed most of the more inflammable fractions, giving the oil a high flash-point, and enabling it to be burnt in ordinary lamps without distillation. In this case also the overlying series is petroliferous, and oilshows on a large scale with explosive discharge of

Photo. by G. B. Reynolds.

The White Oil Springs at Kala Deribid, Persia.
Showing the gently sloping flank of the anticline.

Photo. by G. B. Reynolds.

THE WHITE OIL SPRINGS AT KALA DERIBID, PERSIA.
Showing the steep flank of the asymmetrical anticline.

gas from younger strata are not far distant, *e.g.* Faule Island.

In Baluchistan a somewhat different case of migration into older strata may be observed. The impregnation is only along joint planes and in beds of slightly greater porosity in a compact limestone, while the oil is a dark heavy residue containing sulphur and very little light oil. The shows occur on the flanks of a range of hills formed of limestone, anticlinal in structure, and overlaid by a thick series of shales. It is only at the edge of or beneath the outcrop of the shale that any appreciable production of oil has ever been obtained (*e.g.* Khatan), and the oil is very heavy, contains a large proportion of sulphur compounds, and is accompanied by warm sulphur springs. It seems perfectly clear that we are dealing with the inspissated residue of a partial impregnation which took place before denudation had laid bare the series so deeply, and that now only the all-but final results of inspissation are in evidence to indicate that impregnation of lower strata has taken place. The overlying shales are in places distinctly bituminous, and it is from their outcrop not many miles distant that a bituminous coal rich in pyrites is mined.

A more striking instance of much the same phenomenon, and one that can be more easily and completely studied, is afforded by San Fernando Hill in Trinidad. The hill is formed of an inlier of a peculiar rock called "argiline" by Messrs. Wall and Sawkins, and it forms the core of an anticline in the petroliferous Tertiaries which overlie it. The argiline, though an exceedingly fine-grained rock, has been impregnated throughout, and owing to its homogeneous nature and closeness of grain has been enabled to retain the impregnation under weathering influences for a considerable time. In the numerous quarries opened in this argiline, a crust usually some six to eight feet thick of the weathered material is observed, separated sharply from the part still impregnated; the line between weathered and unweathered argiline crosses the bedding obliquely in many places. At the north-eastern end of the hill sticky inspissated oil has exuded in considerable quantity, so much so that a syndicate was once formed to work it, but after doing some excavation the enterprise was abandoned as unprofitable. Similar attempts are often made to obtain oil where some such deceptive "show" has tempted men of enterprise, but without

geological knowledge, to commence development work, and it is largely from such unsuccessful attempts that the popular idea of the great uncertainty of oil exploitation has arisen.

Another instructive example is furnished by the first well drilled by a company now operating in Trinidad. The well was commenced below the horizon of the oil-bearing rocks of the district, and, after passing at shallow depth through strata with slight indications of oil, entered a thick series of clay from which a certain quantity of gas issued. This gas assisted to puddle the clay, which caved badly, and made it rise in the bore-hole and thus cause great difficulty in the drilling. The clays at this horizon are of great thickness and only contain small, inconstant, and insignificant beds of oilsand. After struggling for months with these argillaceous strata and the gas, the well was abandoned, having reached a depth of only some 500 feet. It was probably the occurrence of gas that induced the company to persevere with the drilling, although they had been warned before the derrick was erected that the geological sequence of strata had been worked out carefully, and that the well would certainly prove a failure.

These instances are merely quoted to show of what practical importance it is that the probability of downward migration of petroleum and gas, even into almost impervious strata, should be recognized.

Another theory that is sometimes expressed regarding migration of oil is that it has been present in some particular area, but has escaped by means of faults in the strata, and so is no longer available nor can be struck in a well. This is one of the many suggestions made about faults by those whose personal or practical acquaintance with geological work is small, but who make use of the idea of faulting as a sort of *deus ex machina* to account for something which they do not understand or have been unable to explain. It is reminiscent of an antique method in geological mapping, the observer when involved in serious difficulties boldly mapping a theoretical fault and starting afresh. In books on the subject of petroleum, when faults are mentioned the word is usually followed by the words "fissures" and "crevices." "Crevice," by the way, is a favourite word with the careless driller who has provided himself with a "fishing-job," and who lays the blame for the disaster upon a "crevice," which, suddenly entered

upon, caused too great a strain to be put upon some part of his string of tools or cable.

Faults, fissures, and crevices are stated to have considerable effects upon the underground storage of petroleum by affording channels which allow the oil to escape upwards, downwards, or laterally, and to have disappeared from the rock in which it was stored.

Let it be admitted at once that faults do not infrequently affect oilfields either favourably or unfavourably, and have often a notable local effect in increasing production. Their effects are purely structural, and will be dealt with in a subsequent chapter on geological structure. As channels for migration of oil to any important extent they do not act, for the simple reason that a "fault-fissure" as the term is used in geological parlance is not an open fissure in the ordinary sense of the word. Open fissures are in any case very rare in nature, and only occur in limestone formations or in hard igneous or metamorphic rocks, and then usually comparatively near the surface. Were any open fissure to be formed in soft Tertiary strata, the pressure would be sufficient to close it very rapidly, while if petroleum were to commence migrating by such a channel the fissure would soon be clogged by inspissating oil and the sand or clay brought with it. The storage of petroleum in any locality necessitates a more or less impervious cover, usually of considerable thickness, and this covering would require to be completely dislocated, a fissure opened and prevented from becoming sealed before there could be any possibility of the escape of petroleum in quantity. Where the covering is largely of soft argillaceous strata such a phenomenon is manifestly impossible. Another point also falls to be considered; even with an oil-bearing series entirely exposed at outcrop, the petroleum contents are dissipated by exudation at the surface very slowly. At the depth of some hundred or even thousands of feet such action into a narrow open fissure could not but be very gradual.

Where one does obtain evidence of a form of migration to which the expression "intrusion" may be applied, is in veins of manjak, which term is used to include gilsonite and its congeners, and ozokerite. Manjak is to an asphaltic oil what ozokerite is to one of paraffin base. They are inspissated oil in veins which have actually been *intruded* usually in a vertical

or highly inclined position from oil-bearing strata below, and the material has consolidated *without reaching the surface.* Occasionally such veins may be found along lines of fault, but all those with which the writer is familiar are either along bedding-planes or along minor slip-planes and joints in thick masses or argillaceous strata. The phenomena associated with manjak veins will be dealt with more fully later; the point to be noted at present is that if petroleum did migrate to any extent along fissures, cracks, or fault-planes, we should find abundant evidence of its having done so in veins of manjak or ozokerite. But these phenomena, though known in many parts of the world, cannot be said to be common occurrences in oilfields, while faults are frequent to a greater or less extent everywhere that earth-movement has been in operation, and there is hardly an oilfield that is without some evidence of faulting.

From all these considerations it will be seen that the migration of petroleum is a very circumscribed action, and cannot be called upon to explain any very widespread phenomena in oilfields. To put it briefly, petroleum goes where it can, but from the very nature of the conditions under which it has been formed and under which it is preserved its migrating movements are checked and hindered in almost all directions. Thus when earth-oils are discovered in any locality, we are almost justified in applying to them the famous conclusions of the gentleman who devoted his life to research upon the subject of the "fiery flying serpents in the wilderness," with special attention to their origin and subsequent history: (1) "They was there all the time," and (2) "they stayed where they was."

Subterranean Storage.—The relative porosity of strata is one of the determining factors in the movements of oil, and the selection of a reservoir rock. Oil will find the nearest available porous strata and will impregnate them. Given sufficient time and pressure it will impregnate, and even to some extent force, its way through, an apparently impervious clay, but it will select the most porous stratum to impregnate. This is the reason that a gas-show, with a slight show of light and perhaps light-coloured oil, is so often struck in a well some little distance above the main oilrock. It is a filtered oil which has gradually accumulated in a porous band, after passing through

the almost impervious cover of the true oil-bearing stratum. In most cases, however, it is only gas that is found under these conditions.

The great majority of oil-bearing rocks are arenaceous, sandstones of all kinds, grits or conglomerates, but some of the world's most famous oilrocks are limestones and dolomites. In the case of calcareous rocks it is probably merely because the limestone affords a porous reservoir that it is found impregnated with oil, just as in a manjak mine a nodule or nodular band of ferrous and lime carbonate, being slightly more porous than the surrounding clay, will contain more evidence of petroleum than the country rock. However, as the occurrence of oil in limestones has been made use of as an argument in favour of the animal-origin of petroleum, it is necessary to examine the evidence carefully. The famous Trenton limestone of North America is perhaps as good an instance as could be chosen. It contains barren areas and areas of partial impregnation, as well as areas where great productions of petroleum can be obtained, and it has been the subject of much research. It has been proved that in the localities where the rock is most productive it is cavernous in structure, containing innumerable small cavities which are often drusy, and which are found full of oil. Analysis has shown that the cavernous variety of the Trenton rock is dolomitized, the dolomitization naturally causing an increase in specific gravity, which connotes a decrease in volume, and thus causes the cavities. The rock, in fact, over wide areas, though sometimes only on selected horizons, has been formed into what may be compared to a sponge, and the oil contents vary in quantity directly with the degree of dolomitization. It is difficult, if not impossible, to imagine any chemical action which will bring about the dolomitization of a limestone and at the same time produce petroleum, and one is forced to the conclusion that the presence of the oil is accidental, and that it has occupied the cavernous limestone simply because the rock afforded room for it. Much of the impregnation, by the way, may be due to downward migration. In this connection we may bring forward confirmatory evidence from the cavernous limestones of Maidan-i-Naphtun and Marmatain in Persia. These are the oil-bearing strata from which the Anglo-Persian Oil Company is obtaining such remarkable productions, and they were first

studied in detail by the writer. They are grey porous limestones, containing innumerable small cavities, generally lenticular in shape and attaining to a diameter of as much as one inch. The cavities are frequently drusy; their presence makes the rock in bulk exceedingly porous.

Careful mapping of the Maidan-i-Naphtun field proved that these are not ordinary limestones, but are of detrital origin; they vary from very coarse breccias consisting of large irregular blocks of limestone and sandstone in a calcareous matrix on the one hand, to thin calcareous sandstones and finally ordinary sandstones on the other. The thinning out of these calcareous masses, becoming sandier and occasionally more argillaceous as they thin out, is beautifully seen. Surface indications of oil occur in these strata even where they have thinned out into bands of sandstone a few feet thick, but the "shows" are greatest where the different bands coalesce into thick masses of calcareous rock. The origin of the limestone fragments, which are often most irregular, is the Cretaceo-Eocene limestone of Asmari, a very thick calcareous formation which is overlaid unconformably by the Tertiary petroliferous series.

These limestones, being of detrital origin, cannot be brought forward as evidence of the animal-origin of oil, as has been done in the case of the Trenton rock. Yet they present the same cavernous and drusy characters. Analysis to determine whether dolomitization has taken place or not has not yet been undertaken, but the rock has all the appearance of a dolomite, and the writer has little doubt about the matter; the drusy cavities certainly contain crystals of dolomite. The conclusion is obvious: the cavernous rock has become impregnated with oil, *because it is the most porous reservoir available* amidst a thick series of gypsum, shale, and mudstone beds.

At Jemsah, on the Gulf of Suez, very similar strata contain the oil-bearing beds, which are again cavernous dolomites.

Spindle Top gives another instance of a cavernous limestone or dolomite containing petroleum in quantity. In this case the impregnation is probably due to lateral migration aided by earth-movement.

It is perhaps not out of place to mention here that limestone oils frequently exhibit some differences from sandstone oils, and though those differences may not be essential, they may be of considerable practical importance. Thus many limestone

oils are noted for the percentage of sulphur which they contain; their outcrops are often marked by sulphur springs and evolution of hydrogen sulphide, while crystals of pure sulphur may be found lining cavities in the oilrock. Spindle Top, Marmatain, and Maidan-i-Naphtun in Persia, and Khatan, Spintangi and Kirta in Baluchistan are instances. In these cases there is reason to believe that the sulphur compounds may not be entirely original in the petroleum, but may be due to the action of the oil and water on sulphides contained in the strata. In oilsands and their associated clays, pyrites and marcasite are not uncommon, but in the limestones of the above mentioned oilfields these minerals are apparently absent. It is possible that the petroleum may have absorbed and incorporated sulphur compounds encountered during its migration to and through the limestone which it now occupies. In the cases of Khatan and Spintangi the shales where the oil originated are full of pyrites in the area where the carbonaceous phase is in evidence, and the Harnai Valley Coal, as the bituminous coal worked in these shales is called, contains a large quantity of pyrites. This is absent at Khatan, but sulphur compounds are present in the oil, and sulphurous springs appear every here and there from beneath the outcrop of the shales.

Parallel evidence can be obtained within the confines of Great Britain; in the west of England where the Carboniferous limestone becomes slightly bituminous in some localities, the fœtid odour of a fresh fracture gives unmistakable evidence of the presence of hydrogen sulphide.

It is not suggested that sandstone oils do not contain sulphur compounds, many of them are unfortunately very rich in this, in oil, undesirable element, but there seems to be some condition affecting oils enclosed in limestone which makes it possible to decompose any sulphides present and to incorporate a percentage of the sulphur in the oil, which percentage naturally becomes more conspicuous as the sulphur compounds are concentrated by the inspissation of the petroleum.

Further research is necessary upon this point, but the suggestion of the effect of environment on the oil after its formation is made here as it may be of practical utility. The same oil that impregnates a limestone in one locality, where it is associated with abundant evidence of the presence of sulphur, may be found in a locality not far distant impregnating

a sandstone, and containing a smaller percentage of sulphur compounds and consequently being of higher quality and better value.

It is to sandstones, however, that we owe our principal supplies of petroleum, and almost every variety of sandstone may be found acting as an oil reservoir.

Here one of the popular ideas of the driller may be summarily dealt with. In oilfield work one is frequently informed that there are oilsands, gas-sands, and water-sands, and that they have essential and different characteristics, while some informants will even go so far as to state that they can tell by examination of a clean sample of sand to which of these three classes it belongs. These are men often of acute observation, and they may be perfectly right for a particular field, or in a particular locality, but to generalize, in one or even several oilfields from the evidence, and to expect the generalizations to prove true of another field, perhaps in a different country, is notoriously dangerous. True, in one field the oil-bearing horizons may be composed of a certain kind of sand of characteristic coarseness, colour, contour of grain, and porosity, while gas or water may be found in the same locality in arenaceous strata of different types, but a sand may change almost entirely in character within the space of a few hundred yards, and yet remain none the less an oilsand, gas-sand, or water-sand as the case may be. Proceeding down the flank of an anticlinal flexure, or down the pitch of a dome structure, what was the oilsand near the crest may be found destitute of oil and full of water.

Again, some sandstones, especially those with calcareous cement, may be so compact as to be hardly capable of containing appreciable quantities of oil, but may contain gas. But when one considers the conditions under which such sands have been deposited, it becomes obvious that the calcareous cement may vary in quantity in different localities, and the porosity of the rock may vary as much. Thus the same sandbed may be rich in oil at a comparatively short distance from where it was merely a gas-sand. A low-lying shore, such as may be seen on the eastern coast of Trinidad, is an object lesson in arenaceous deposition. There every gradation from a shell-bed, formed almost entirely of fragments of broken shells, to a pure siliceous sand, a muddy sand or a sand containing vegetable matter, which will eventually be a carbonaceous sand,

may be seen accumulating under the action of waves and tides. Each variety will differ from the others in size and contour of grain, chemical composition and porosity, and all are being formed simultaneously within a distance of, perhaps, less than a mile of coast line.

It cannot be too clearly stated and understood that *an oilsand is a sand containing oil, a gas-sand one containing gas, and a water-sand one containing water.* Remove the contents, and they are no longer entitled to the names, though they may still be mapped geologically and designated as the horizons of such and such oil-, gas-, or water-sands.

Contour of Grain.—On the subject of the contour or shape of the grains in an oilsand there has been some confusion of opinion. Mr. A. Beeby Thompson in his book on the "Oil-fields of Russia" gives microphotographs of sands from Baku oilwells, calling attention to their fairly well-rounded character, on the strength of which he suggests that they are wind-blown. On the other hand Professor Clifford Richardson in his book on "The Modern Asphalt Pavement" gives microphotographs of the sand extracted from the asphalt of Trinidad's famous Pitch Lake and washed, calling attention to the sharpness of the grains, on the strength of which he suggests that the silica has been deposited from solution. Now the sand grains in Trinidad asphalt from the Pitch Lake are derived, as is the bitumen, from the La Brea oil-bearing group, on the outcrop of which that great asphalt deposit has been formed. Here then are two authorities who have examined the silica grains from different asphaltic oilsands, one calling special attention to the roundness of grain, and the other to the sharpness. This is quite sufficient to prove that oilsands differ considerably in the matter of the shape and contour of grains, but in this particular case the writer is unable to agree with either Mr. A. Beeby Thompson or Professor Clifford Richardson on the evidence which they have brought forward and figured. The Baku sands are neither so well-rounded nor so evenly graded as typical wind-blown sands; it is more probable that any special degree of smoothing or rounding which these grains exhibit is due to the attrition they must necessarily have experienced in the well before being brought to the surface. In a flowing oilwell, where sand is brought up with the oil, there must be a great churning up of the siliceous material,

quite sufficient to add a polish to the grains. Mr. Thompson's further suggestion that the sharpness of these grains may have caused an epidemic and rapidly fatal disease among shoals of supposititious fish, the carcases of which provided the raw material for the formation of petroleum, hardly bears out his contention as to the sands being wind-blown.

In the case of the La Brea oilsand, the grains are certainly neither so sharp nor so distinctly broken fragments of crystals as to suggest deposition from solution. It is a very ordinary water-borne sand.

There is, however, no reason why wind-blown sands or any other kind of sand should not become impregnated with oil: any porous rock will serve.

Porosity.—Porosities naturally vary very greatly in oil-bearing strata, and as it is on the thickness of an oilrock and its porosity that production ultimately depends, the subject is worthy of careful study.

The voids in a rock may be as much as 40 per cent. by volume, but that is exceptional and unlikely to be met with. Percentages of 20 and 25 of voids, however, are not by any means rare occurrences in sands, and given that the voids are completely filled with oil, a prolific production may be expected. Too porous an oilsand has its disadvantages, since on being struck in a well the cohesion of the stratum is liable to be completely broken down, and quantities of sand brought up with the oil. This may cause choking of the casing, the wearing away of flow-heads and caps put on to check or control the flow, and in extreme cases the derrick may even be half buried in sand.

In Baku the quantity of sand brought up by flowing wells has been a cause of great trouble and expense, and in California and Trinidad similar difficulties have been encountered. The oilsands of the latter colony have been analysed by Professor Carmody, Government Analyst and Director of the Agricultural Department, samples being taken from outcrop for the purpose. Percentages *by weight* of from 15 to 18 of inspissated petroleum have been recorded from outcrops of the Rio Blanco oilsand. By volume this would mean nearly three times as much, so it may readily be understood that in some cases the surface of the outcrop actually shows signs of flow. Strata in this case cannot be broken by a hammer, being too soft, but small fragments

can be twisted off in the fingers and rolled into pellets. Where the oil is not inspissated the percentage both by volume and weight will not be so high, but it is evident that strata so rich in oil will break down easily when struck in a well. The experience of those companies who have drilled into the Rio Blanco oilsands is that sand is always tending to fill up part of the casing, and the wells must be constantly cleaned if their production is to be maintained.

The La Brea oilsands, the youngest oil-bearing rocks of Trinidad, also contain a very large percentage of petroleum, and it does not require the experience of drilling near the Pitch Lake to prove that the cohesion of the rock is very easily broken down; the Lake itself is sufficient evidence. The winning of oil from wells drilled to this oil-bearing group will always be subject to great difficulties on account of clogging of the casing by heavy oil and sand, and the wells will require constant cleaning out.

The most satisfactory oilsands are those which are sufficiently compact to maintain their cohesion even when the well is flowing. The greatest productions are not obtained from such sands, but wells drilled into them have a longer life and are worked much more economically.

Paraffin oils, perhaps because they are as a rule of lighter gravity than asphaltic oils, seem to disengage themselves more easily from the sands, and do not, as a rule, carry so much sand with them. This, however, may be partly due to incipient paraffination, the deposit of paraffin scale in the sand helping to maintain the cohesion of the rock. The sudden relief of pressure and consequent lowering of temperature when a prolific well is brought in in a paraffin-base oilsand must cause solid paraffin to be deposited. If a well in such circumstances be not carefully looked after, its life may be shortened considerably by the sand near the bottom of the bore-hole becoming completely clogged with solid paraffin.

The great advantage that limestone has over sandstones as an oil reservoir is that it does not break down and choke the bore-hole, and another advantage of almost equal importance is that it is possible to torpedo a limestone well, the production of which has fallen off badly, by exploding a charge of nitroglycerine at the bottom of the bore. This usually results in giving the well a new lease of life. It is seldom of any

use to torpedo a well in sandstone, even if the rock be fairly hard.

Oil occurs not infrequently in shales and clays where they have some degree of porosity, but the yield of wells drilled into such strata is always small and the petroleum accumulates very slowly. The oil is naturally well-filtered, and light in such conditions, but production is seldom sufficient to ensure a commercial success. In Java wells have been drilled into oil-bearing shales, yielding an excellent oil, but not in sufficient quantity.

There is some evidence suggesting that an oil may, under certain conditions, prepare its own reservoir by the removal in solution of cementing material in a rock. This probably applies only in the case of calcareous cement, and may take place only within the zone of weathering, but as that zone may extend downwards for some hundreds of feet the results might be important.

On the southern coast of Trinidad there are many sections where the cliffs have been cut back by marine denudation, leaving a very gentle slope of clays usually much land-slipped —a plan, in fact, of former landslips. The strata dip steeply, and contain numerous thin beds of calcareous sandstone which stand out in lines above the clay surface, but are often discontinuous.

These sections, though washed twice a day by the tide, reek with the odour of petroleum, and a close examination shows that similar small reefs of brown oilsand are contained in the clay. These oilsands are seldom more than a foot or two thick, and they resemble the calcareous sandstone reefs in every way, except that they contain little or no lime, and are very much softer and consequently less prominent. They are quite full of petroleum which exudes steadily and slowly, forming films upon the pools of water left by the receding tide. The oil is light, and is accompanied by very little gas.

Washed about on the shore, and sometimes embedded in the clays near the small reefs of sandstone, are large botryoidal masses of calcium carbonate. These masses are dark in colour owing to the inclusion of a proportion of clay, but the calcite is well crystallized, the crystals radiating from the centre of each rounded mass. These botryoidal masses are quite different from the ordinary fine-grained calcareous concretions of the

clay. They occur in many parts of the island, but always near the outcrops of oil-bearing strata. Unfortunately, they are generally found loose, washed out of the clay.

In one locality near Galfa Point in the Cedros district, a bed of sandstone some six feet thick is exposed among clays on the foreshore. Part of it is hard and calcareous, and part comparatively soft, brown in colour, and highly petroliferous. In the calcareous portion petroleum is only seen along joints and bedding planes. The calcareous cement does not occur like a concretionary mass, but is quite irregular in outline and appears as if it had been attacked and eaten into by the petroliferous portion of the rock. Botryoidal masses of calcite are present close at hand, washed out of the clay series.

The suggestion is made that these botryoidal masses represent calcite that has been dissolved out of the sandstone and has crystallized out in the softer clay, thus leaving room for the oil to impregnate the sandstone beds. In the zone of weathering, carbon dioxide and water might be present in sufficient quantity to attack a calcareous cement, but the action must have taken place beneath the surface to allow the dissolved calcite to concentrate under concretionary action and crystallize out.

What part the petroleum and its accompanying gases can have taken in such an action it is difficult to determine; with the help of water they may have supplied the corrosive solution. The point to be noted is that these phenomena have only been observed where oil-bearing strata are present. Further study of such evidence may throw light upon the movements and storage of oil, and especially upon the effect of oil and water in combination upon limestones, and may help to explain the selection of beds to form oil reservoirs, even when they are surrounded with almost impervious strata.

There are many minor points with regard to the underground storage of petroleum which might be cited, but all depend upon the principles already laid down, the selection of the most porous or potentially most porous stratum available. The migration through practically impervious beds must be very gradual, but, given sufficient pressure, it is sure, though it is probably only the lighter constituents of the mixed hydrocarbons that are able to migrate for any considerable distance.

CHAPTER IV

LATERAL VARIATION

HAVING now considered most of the more important theoretical questions concerned with the formation, migration and storage of petroleum, let us turn to the more practical matters of how oilfields are to be found, and how we can make as sure of them as possible. In the next five chapters facts as discovered and studied in the field will be considered, and theory as far as possible eschewed, while methods of approaching the various problems which have been found of value by the writer will be discussed.

The geologist whose task it is to prospect a new country, or a new area in a well-known country, for petroleum, will do well to prepare himself by the collection of as many previously known facts as he can find bearing upon the particular area, and by *the deliberate abstention from reading any opinions, generalizations, or theoretical matter* that have been published about it. By this the intention is not to cast aspersions upon any work done previously by explorers, geological surveyors, or travellers with a taste for science, but simply to enable the "field-student" to start work with a perfectly open mind. The line between opinion and fact must be drawn rigidly. There are very few countries nowadays which are not, at least, partially known geologically, and geological surveys, even if only of a pioneer type, have done much excellent and sometimes even detailed work in many parts of the world; but the generalizations into which the pioneer geologist is inevitably tempted are dangerous things, and lest they should impress, oppress, or antagonize his mind, the field-student will do well to know nothing about them. Ready-made generalizations fit the facts no better than ready-made coats fit the body; they are the bane of original work, and unless the observer can improve upon

what has been done before, and can see a little deeper into the geological puzzles that await him than has been done by previous workers, he is unworthy of his task.

To get at recorded facts, however, without absorbing opinions is a matter of difficulty, but for this reason the writer would emphasize all the more the necessity of an open mind. After field-work has been done, new facts collected and correlated, new areas mapped, then comes the time for reading, for testing theories and opinions in the light of new discoveries, and one's own theories in the light of how such or similar facts appeared to trend in the minds of others.

Let a small scale geographical map of the country be procured (if there be such a thing as a geological map it will also be necessary), and let the prospector sit down before them and study them, noting roughly on each such essential facts as the ascertained or reported occurrences of surface indications of oil. If only an unknown or unprospected district of a country is to be examined, a map of the said district will *not* suffice; a map of the whole country, perhaps with portions of neighbouring countries, is essential. The "field-student," as the writer prefers to call one who reads the rock rather than the printed page, who travels through countries rather than reference libraries, is now in search of a few general ideas. What if they prove wrong? It is no matter; they will be tested in the field.

The orientations and extents of the principal mountain ranges, the courses of the main rivers, and the character and configuration of the coast-line, if any, are naturally the first points to be noted. The first of these will probably give a very clear indication of the directions of the principal earth-movements to which the area has been subjected, or at least will show that one of two directions at 180 degrees is the main direction of the principal or latest movement.

The courses of the rivers can as a rule be divided into "consequent" and "subsequent" portions, and will thus in connection with the mountain chains afford considerable assistance in determining roughly the main strike-lines of the country.

A study of the coast-line should indicate what parts are rocky and what parts flat and low-lying, and the presence of any delta of considerable size will be detected at once.

If the oilfields to be searched for or examined are in Tertiary strata, the methods of arriving at general ideas are simple, as it is only the latest earth-movements that have to be considered. If series older than the Tertiaries are to be examined the enquiry becomes more complicated, and it may not be possible to arrive at any general ideas of importance by a preliminary study of the map, unless some geological data are available. Most of the world's great oilfields, however, are in Tertiary strata, and of oilfields yet to be discovered in such countries as Galicia, Roumania, Russia, Egypt, Turkey, Persia, Baluchistan, India, China, Venezuela, Columbia, Brazil, Argentina, and Mexico, we may safely assume that very few, if any, will be in rocks older than the Cretaceous formation; so for the present let us consider that a Tertiary Series is to be prospected.

Some general ideas as to the probable main structural lines of the country having been obtained from the map, and the approximate positions of known and reported indications of oil noted on it, the prospector must ask himself why the oil is found in such localities and how it got there. These queries may take long to answer, or to obtain any light upon; when they have been answered, the prospector will be in a position to determine where else petroleum is likely to be found. The reason for considering such queries and attempting to find answers to them is that the general question of the occurrence of petroleum should not be lost sight of when practical field work is begun. To search for favourable structures in areas which are apparently outside the belt of country in which it is possible to find oil in paying quantity is not only a waste of time from the practical point of view, but, if experimental wells be drilled as the result of the prospecting work, other instances will be added to the long list of failures which have made the general public look upon oilfield work as on much the same level, in regard to risk, as gold mining.

The prospector is now ready to familiarize himself with the lithological characters of the rock with which he has to deal. For this purpose several lengthy traverses across the main strike-lines of the country are necessary, and also, if possible, one or more roughly along the strike. The object is not only to study the series as a whole, but to determine, if possible the direction or directions of lateral variation.

This is primarily a more important matter than the study of structure, and accordingly it is considered first. In the author's experience are only too many instances of the following of structure in oil development work, while the lateral variation in the strata was neglected or lost sight of.

In many cases the working out of the directions of variation in the field may be a laborious task, necessitating the determination of the stratigraphical relations of different groups, but in some cases a clue may be furnished at once from the preliminary study of the map. There may be a great river in the country with a well-marked delta, and the evidence may point to this river having been represented in Tertiary times, while the ascertained main directions of earth-movement, or earth-waves, may indicate in what direction, laterally or otherwise, the course of the river has probably been changed between Tertiary times and the present day. In Persia, Burma, and Baluchistan, this method of approaching the subject proved of great value.

Deltaic Conditions.—If deltaic or estuarine conditions on a large scale can be proved to have occurred during the Tertiary Series in question, rapid and remarkable variations both along and across the main strike-lines are almost certain to be revealed. The field-student must look for constantly alternating types of deposit, *e.g.* shales or clays alternating with sands. Beds of undoubtedly marine origin, fine clays, marls and true limestones, must be differentiated from litoral or deltaic deposits. In every case when examining a bed the geologist must consider under what conditions it has been formed. The only satisfactory method of arriving at a conclusion on such a point is to consider under what conditions he has seen similar beds being formed at the present day, and failing such direct evidence from his own experience, he must consider under what possible conditions could such a bed be formed. In such an enquiry there is no piece of evidence that is too insignificant to note down. It may be that long afterwards much importance is found to attach to items of information jotted down in note books, or better still on the field maps, items which at the time seemed to be entirely insignificant details. The presence of gypsum or selenite in the clays, of glauconite in the sands or argillaceous sands, and of remains of terrestrial vegetation in any bed, must always be noted. These all point to estuarine or deltaic conditions.

In a general way the main directions of lateral variation may be indicated from the very start by the records of former observers, *e.g.* the presence of thick clays or limestones in one district, and of coals or lignites in the same series in another, at once suggests that some variation may be expected in such and such a direction, even though the horizons of the particular deposits have not been ascertained.

In the deltas of great rivers, channels are continually changing their courses, so that sand-bearing currents trespass upon mud-flats, and the coarser and more arenaceous detritus thus alternates with the finer and more argillaceous. Sand-bars are continually being formed between sea and delta, cutting off lagoons or salt swamps. These sand-bars also are subject to sudden modifications through the action of tides and currents: they may be extended and increased, pushed forward or thrown back, cut off to form shoals or completely swept away. And with them the fate of the lagoons which they protect is inseparably bound up. They may be filled up with detritus to form solid ground, or may pass through a stage of mangrove swamp to become a forest-lagoon, a forest growing at or even under sea-level, where terrestrial vegetation flourishes, dies and accumulates in masses which, under favourable conditions, will in time be represented by coal or lignite seams or petroleum. Any slight set-back in deposition, any temporary gain of subsidence against sedimentation, and the lagoon will be invaded by the sea, the vegetation killed, though perhaps not washed away, and marine sediments may be deposited above the remains of forest or swamp growth.

Speaking generally, however, a delta is always advancing in one direction, in spite of the many deflections of the main river-channels. A delta in fact means a victory of sedimentation over subsidence, and in any area where deltaic conditions can be proved to have existed for a long period, littoral sediment will be found to have advanced over more purely marine or pelagic deposits. Set-backs no doubt frequently occur, owing to periods of more rapid subsidence, but a delta stands for continuous deposition, and till checked by a movement of upheaval which is sufficient to enable the river to denude its own deposits, or by the encounter with powerful ocean currents, it must continue to advance.

In such circumstances it is obvious that rapid lateral

variation must occur somewhere at every horizon. In some cases the variation is very remarkable. The Tertiary Series in Trinidad, formed as it is largely of fluviatile, deltaic, and estuarine deposits at the mouth of a great river, which is now represented by the Orinoco, affords some very striking instances. The island is situated on the margin of a continent with the deep Atlantic basin not far to the eastward, and the strata in the Tertiary Series represent a continual struggle between pelagic and deltaic strata, with the latter gradually becoming predominant, and variation on the same horizon is remarkably well shown. Thus near the Cunapo lignite field it is possible to pass on the same line of strike from a lignite seam through conglomerates and sands representing a littoral deposit into muds, fine clays, and finally a marine limestone within a distance of three or four miles. The lateral variation in that island is very complicated, and has not been fully worked out on all horizons as yet, but it seems to have been lost sight of by many of the energetic oil-prospectors who have visited the Colony.

In examining a deltaic formation, then, variation in almost every direction may be observed locally, but the algebraic sum of all variations, supposing it were possible to measure these effects, would point to some general direction.

The concrete bits of evidence to be looked for are the splitting up and thinning out of sandstone beds, the decrease in coarseness of arenaceous sediment, the passage of sandstones into thin calcareous sandstones among argillaceous rocks or finely laminated alternations of sand and clay, the oncoming of finely laminated clays without gypsum, and the directions in which they thicken. Similarly the development and thickening of beds of calcareous marl, whether foraminiferal or not, and the first signs of true limestone bands must be noted. A shell-bank, formed of a mass of broken shells on a shore line, must not be considered as a limestone, even though it may be composed almost entirely of carbonate of lime; it has been formed in the same manner as a littoral sand. Again, the thinning and splitting up of lignite seams among banks of sand and conglomerate, which were the bars between sea and lagoon, the passage of such seams into carbonaceous sands or clays, and the passage of shales into underclays and leaf beds, are of great importance. All these phenomena, if observed carefully,

will give definite information as to which side the land lay and which side was open sea.

All evidence of shallow water conditions or sub-aerial conditions such as false-bedding, ripple mark, sun-cracks, rain-pittings on fine sands and clays, and in some countries deposits of lateritic type, which were weathered and oxidized at the time of formation, and represent what were at one time land-surfaces, are of value.

The directions of currents can frequently be made out from the arrangement of the longer axes of the pebbles in a conglomerate, and especially in clay-gall beds, and what have been called "clay conglomerates," which consist of pebbles of more or less soft argillaceous beds in a sandy matrix. This type of deposit is caused by a sand-bearing current impinging upon a partially consolidated clay or mud deposit and breaking up the bed, rolling the fragments into pebbles, and often bending the pebbles so formed. They pass, by the gradual decrease in the size of the argillaceous fragments, into sandy clays. Beautiful examples of this type of deposit can be seen on the western coast of Trinidad, and may be photographed in cliff sections, where the actual initial bending up and breaking of the argillaceous bed is sometimes observed, the current action having been checked exactly at this stage. In Burma also, and in Persia, where the detrital limestones have thinned out and become muddy and sandy, bands formed in this manner are to be seen.

Finally, fossil evidence must be studied in connection with these variations, but the fossils must not be taken from the mixed faunas formed in littoral beds, where specimens from littoral, laminarian, and pelagic zones are washed about on the beach together, but from the actual deposits in which or on which the organisms lived. Oyster beds, for instance, may be noted as important; foraminiferal beds, thick clays containing lamellibranchs with joined and closed valves and gasteropods in perfect preservation, and assemblages of fresh and brackish water forms are all of help in determining directions of variation.

In well-exposed sections on river banks, sea cliffs, road or railway cuttings, and, if the ground be not too much obscured by vegetation, in any hilly ground, it is possible to study all these phenomena and to derive from each some

link in the chain of evidence as to the side on which sea and shore respectively lay, while the deposits were being formed.

When this study is extended over wide areas and over many horizons in a thick series, the course of a delta can be made out with considerable accuracy at each successive epoch, and it can be shown to have pushed forward its littoral sediment, now rapidly, now slowly, with recurring intervals of retreat, and with perhaps slightly diverging directions at different times, but over all with a steady inevitable advance over the more characteristic marine sediments with which it was contemporaneous.

The Pegu Series of Burma, ranging from the Eocene far up into the Miocene according to our subdivisions of Tertiary time, furnishes perhaps the most conclusive evidence of the advance of a delta that has been worked out in any detail. All the phenomena of deposition mentioned above can be studied in this series, but for the most part the thinning out and splitting up of sandbeds, and the simultaneous thickening of clays, are sufficient to make the directions of variation quite clear, so that we are now enabled to elucidate the history of the series in almost all parts, and to give an idea of the conditions under which each particular bed was formed. The boring journals of oilwells have been of the very greatest assistance in establishing the history of the Pegu Series point by point.

A great river flowing from the northward entered a land-locked gulf, and hugging the western shore, gradually filled it up by its advance. Much of the axis of the Arakan Yomas was already land when the Pegu Series began to be deposited, and along the western shore thus formed great littoral sandstones with much evidence of terrestrial vegetation were deposited. On its eastern side the deltaic deposits were intercalated with truly marine beds. The advance of the deltaic deposits was not steady, but subject to many checks and retreats. During some of the checks vast accumulations of vegetable matter were formed in the swamps and lagoons near the river-mouth, to be afterwards buried under marine deposits of the invading sea or covered by coarser estuarine detritus as the delta was pushed forward. Thus in Lower Burma the oldest strata of the Pegu Series are entirely or almost entirely

marine, while deltaic and even terrestrial conditions existed simultaneously in parts of Upper Burma. Earth-movement was in evidence, but not very active.

When the delta passed beyond the shelter of the western coast its course was to some extent deflected by ocean currents, but it continued to advance over the marine sediment. Now, after many changes of level, and the deposit of an overlying fluviatile series (which is usually unconformable to the Pegu Series, but also has a marine phase that cannot but be conformable somewhere to the Pegu Series), the Irrawaddy has fallen heir to the former great river; and though it has a somewhat different course the general direction is the same, and we can still study the advance of a delta at its mouth.

In other countries the advance or retreat of deltaic fans of detritus may also be proved, but few cases are so simple as that of Burma. In Trinidad, for instance, earth-movement on a fairly large scale supervened during the deposition of the Tertiary Series and caused certain complications, so that the upper strata lie in a violent unconformity across the denuded strata of Middle Tertiaries. Yet the main directions of lateral variation can be proved with some degree of accuracy. During the deposition of the earliest Tertiary strata, sedimentation was advancing from the south-east, while marine conditions persisted for a longer period in the south-west. Towards the middle of the Tertiary period sediment was poured in from the south and west, and the arenaceous detritus is intercalated with and passes into pelagic strata to the north and north-east. Then followed a period of retreat when the advancing arms of the delta barely held their own, and fine clays and foraminiferal marls were deposited above strata of deltaic origin. Finally, sedimentation advanced again, and arenaceous strata were deposited by many currents flowing in various directions, east and west and north. The presence of islands of older strata, and the inception of a folding movement acting in a northerly direction, introduced many complications, but the main branches of the delta can be followed out, and seams of lignite and bands of oil-bearing rock at various horizons mark approximately the localities where accumulations of vegetable matter in forest lagoons or swamps were formed.

The same principles may be applied to the elucidation of the history of the Tertiary Series in many other countries, but

it would weary the reader to enter into elaborate details of the evidence from one country after another that has served to confirm the theory and to associate oilfields with deltaic conditions.

The point of all this insistence upon the importance of studying lateral variation and determining the boundaries of a deltaic formation is simply that the probable petroliferous belt may be recognized. If oil is to be drilled for, it is as well to look for it as near as possible to areas where the conditions for its formation were favourable. On the one hand may be littoral and terrestrial beds where the carbonaceous phase is in evidence, on the other marine beds beyond the confines of the delta. Somewhere between we may hope for an area where the necessary alternations of arenaceous and argillaceous sediment are present, an area not too far from localities where accumulations of vegetable matter have probably been formed, buried, and sealed up. In that area we must seek for favourable structures to concentrate and retain the petroleum.

Much excellent work of competent geological surveyors, much arduous toil in opening up new districts and transporting plant to them, much fruitless expenditure of money and time could have been saved, had the facts concerning lateral variation been carefully studied and mastered.

It is, of course, a commonplace of geology that lateral variation occurs in rocks of all ages, but unfortunately in Britain, the birthplace of stratigraphy, the variations in most formations and series, with a few notable exceptions, are not very great, and much correlation of strata, it is to be feared, is still attempted chiefly on lithological grounds. Where we have evidence of continuous deposition on a large scale, and deltaic and estuarine conditions, as we have in the Carboniferous Formation, it has taken decades of field-work and controversy, and volumes of scientific papers written and discussed before it has been possible to arrive at a conclusive general idea of the conditions and variations. Even at the present day we find a classification based upon subdivisions established in some districts in England, including the well-known Millstone Grit, forced upon Scotland where such a classification is neither natural nor of practical benefit; and still "palæontological breaks" are inserted in a continuous series in order that a universal general arrangement may be adhered to. Similarly

we have seen our local subdivisions such as Eocene, Oligocene, Miocene, and Pliocene forced upon other countries where their only significance is chronological, and where no natural groupings can be made to coincide with them. In our turn we have adopted Continental subdivisions, *e.g.* in the Cretaceous Formation, which are at the least very doubtfully applicable.

But if lateral variations during continuous deposition can be proved to be common and distinct among the primary and secondary formations in the Tertiaries almost all over the world, they become even more frequent and impressive, because it is those Tertiary strata which have emerged comparatively recently from beneath sea-level that we know; the great uniform Tertiary deposits, which perhaps future geologists will examine, are still beneath the waves. That is to say, we know only the margins of the Tertiary formations, and it is precisely along land-margins and on the fringes of continental areas that lateral variations must naturally be greatest.

We must take variation, then, as the rule and not the exception when studying Tertiary strata, and must not attempt the correlation of distant areas, as the author has often seen done, by similarity of lithological characters or the presence of some particular mineral or minerals. Such evidence only means similarity in the conditions of deposition, a similarity which during progressive sedimentation must migrate from one area to another. Thus oil-forming and oil-bearing conditions may be transferred from the lower beds of a series to the upper beds as we proceed from one province to another.

CHAPTER V

GEOLOGICAL STRUCTURE

It will be noticed that what is usually considered the most important matter in oilfield work, the study of geological structure, is given a secondary place. This has been done, not because its importance is not fully recognized, but because the study of lateral variation comes first naturally, and may render unnecessary a great deal of detailed work in discovering and mapping favourable structures. The field-student has now advanced sufficiently in his knowledge of the country which he is examining to be able to predict in what districts, and possibly also at what general geological horizons, conditions are favourable to the formation of petroleum. His next task is to discover in the indicated districts suitable structures to contain and preserve the petroleum from inspissation, and to ensure sufficient concentration to make paying productions probable.

Earth-movements.—The elucidation of geological structure naturally depends on a study of the earth-movements that have been experienced. Here, again, an examination of the general map of the country is essential; it is advisable to get a broad view of such evidence of folding, faulting, and unconformabilities as has been obtained before details of structure are attacked.

In the preliminary traverses made to gain an insight into the lateral variation, the geologist has doubtless obtained some evidence of folding and the direction of folding movements. In many cases only one earth-movement will require to be considered; in others two, or even more, of different ages, directions and degrees of severity may have to be distinguished and delineated. Earth-movements are instances of relative movement, but as a rule it will be found simpler to consider them as movements in a definite direction towards some central

axis of folding, the force being applied tangentially to the earth's crust. There is no structure produced by flexuring or faulting that cannot be explained by the application of this simple principle.

The movement to be considered, then, resolves itself into a horizontal push, and in the majority of cases the direction is from the seaward towards the mountain ranges. Again, the oldest strata exposed will be found as a rule in the heart of any axis of folding that may be present. This gives another method for determining on *prima facie* evidence the direction of movement.

Where flexuring attains to great dimensions, and a series of well-marked parallel folds is produced, the steep sides of asymmetrical folds will be found almost invariably on the side from which the movement took place, and vertical or even inverted limbs of flexures are not uncommon in such circumstances, even among comparatively young Tertiary strata. This is all in accordance with the development of a geanticline, and the production of a facher or fan structure, in which the axial plane of the central fold is vertical or nearly so, and the axial planes of the sharp flanking folds dip towards the central axis. As one recedes from the central axis of folding, the flexures gradually become less sharp and more symmetrical, till finally they may be represented by small gentle undulations or elevations which affect the dip of the strata so slightly that the pocket clinometer may not be sufficiently accurate and sensitive to prove a general dip in any one direction. In both Persia and Burma there are excellent examples of a series of flexures rapidly decreasing in sharpness as we recede from the central axis of folding.

Thus when a wide area is to be examined there is usually little difficulty in determining the direction of movement, and after a traverse across the main strike-lines of the country it should be possible to predict where gentle folds should be in evidence, where sharp or asymmetrical flexures, and where inversions of the steeper limbs of flexures may be expected.

The age and duration of the earth-movements is another matter of great importance. In some cases it will be found that movement has proceeded fairly steadily during the deposition of a Tertiary series, causing older strata to be elevated on the crests of flexures, brought into the reach of denuding forces and

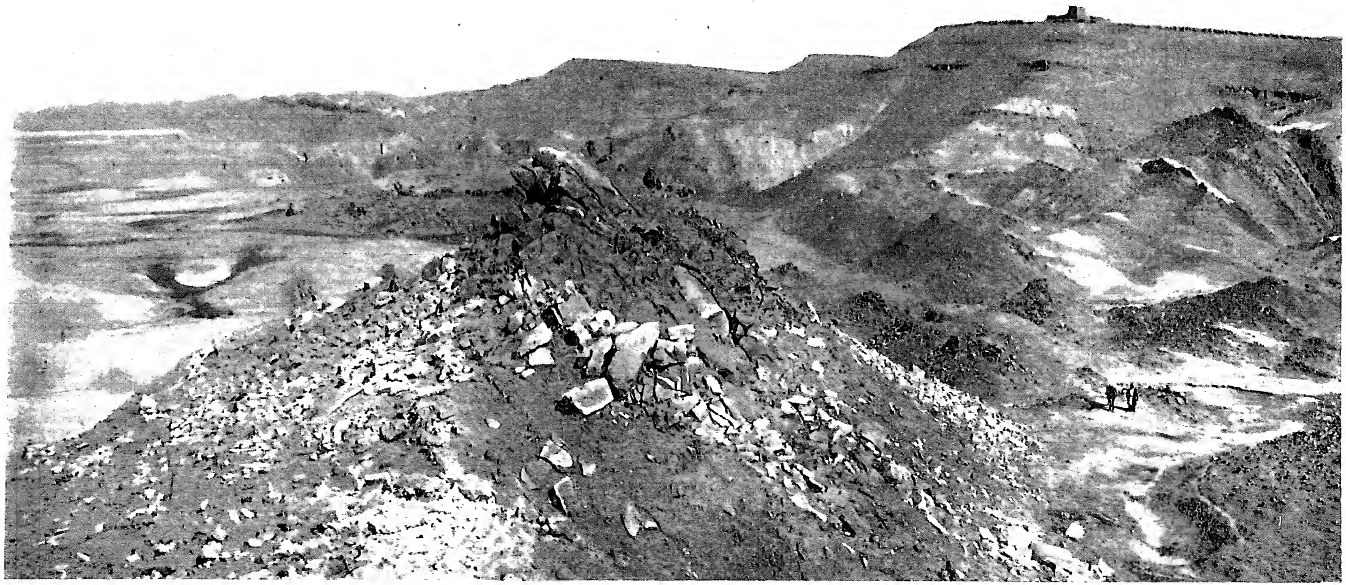

Photo. by G. B. Reynolds.

Scene in the Persian Oil-fields, near Kala Deribid.

actually denuded, while continuous deposition was proceeding in the synclines. The results produced are violent unconformities along certain lines, with the unconformability dying out laterally, while the older strata may be seen in localities sharply folded and overlaid conformably by successive younger strata in which the dips decrease steadily upwards, the uppermost beds perhaps being practically horizontal. The best instance of this that has come under the writer's observation is in Persia (cp. Plate VII), where the movement has been in operation since early Miocene times and is probably still continuing.

In other cases the movement may have been long-continued, but not continuous, so that at several distinct epochs, separated by intervals of quiescence, it has been rapid. The results will be the production of local unconformabilities at different stages, but these unconformabilities may die out laterally within a comparatively short distance, and must not be treated as if they were universal. Great lateral variations in the strata will be caused under such conditions. Sind and Baluchistan afford a good instance of this. In the records of the Geological Survey of India dealing with this province it will be seen that a great number of types of sediment are represented, and very frequently they are separated by unconformabilities. The unconformabilities in this case are almost entirely of local importance only; there is great lateral variation, but there has been little denudation of previously formed beds throughout the series from early Eocene up to perhaps middle Miocene.

In other cases definite periods of folding movement may be made out, and the relative ages of each can be determined by the effects upon series of different ages. This is the case in Burma, where one movement has been detected that affects the Pegu Series and earlier strata, while another and much greater movement in a different direction affects not only the Pegu Series but the younger Irrawaddy Series lying unconformably upon it.

In studying earth-movement it must be remembered that faults are part of the movement just as much as flexures. A fault is merely a special case of folding, where the elasticity of the strata or the amount of "load" is not sufficient to prevent dislocation. Theoretically a fault may always be replaced by a sharp monoclinal bend, and the passage from one

into the other may often be seen. It has too often been the custom to think of a fault as something quite apart, and to map a fault—to use a metaphor from whist—as one would play a trump, not following suit. The author has known faults to be recklessly strewn about a geological map in this manner, when the presence of one could not be justified without the mapping of two or three more which were entirely theoretical, for which no evidence could be obtained, and of which the amounts and directions of throw were purely conjectural. From such methods it soon arrives that when any structure has not been elucidated properly, the remark will be made "there must be a fault," and the puzzle is deemed to be explained. A fault would thus become a sort of make-shift to get faulty observers out of trouble. But the effect is just the opposite; such methods soon affect their own cure by involving the geological surveyor in a net-work of physical impossibilities, from which the only escape is to begin the mapping all over again.

Faults are really very simple matters, and they obey physical laws just as folds do. They must, therefore, only be mapped when justified on physical grounds, and no fault must be recorded of which at least the direction of throw, if not some estimate of the actual amount of throw, can be given.

Structures Favourable to Concentration of Petroleum.—With these preliminary remarks we may pass to a consideration of the structures most favourable to the underground concentration of petroleum. It is usual in books upon the subject to give a list of the various structures which have been tested and proved productive, and a great number of different classes of structure can be described. But any one can be assigned to one of a few main types. Anticlinal structure and petroleum are associated in the minds of all who have studied or worked in oilfields, and though petroleum can be proved to occur in almost every known structure, in the vast majority of cases some form of anticline is present in a successful field.

Dome Structure.—It will be admitted generally that the most favourable structure of all is a dome or quaquaversal, with gentle dips near the summit and steeper dips upon the flanks, which again pass gradually and steadily into a position of horizontality, so that a large area can be included as properly

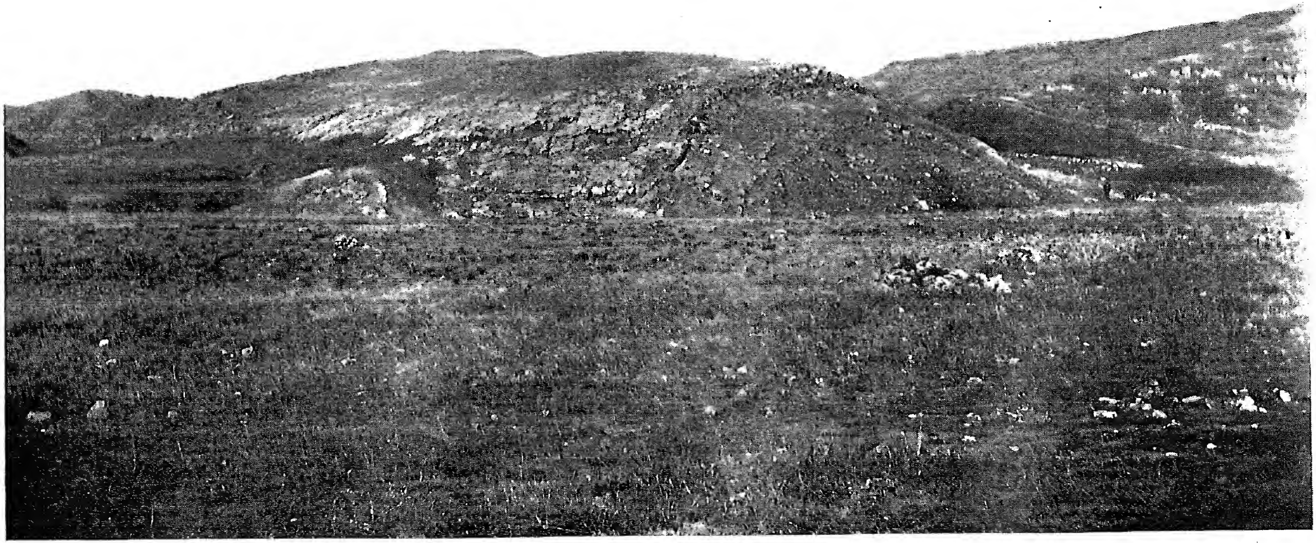

Photo by J. Holland.

An anticline in the Maidan-i-naphtun Field, Persia.

belonging to the dome. This is merely a special case of anticlinal structure, an anticline with pitches of the axis away from a central point.

A broad round dome is very rare in nature, as it almost necessarily requires more than one earth-movement for its formation. Elongated domes, however, are fairly common and there are few anticlines that have not in one or more localities some trace of dome-structure. Spindle-Top is probably an isolated dome of breadth approximating closely to its length, though the evidence does not seem ever to have been recorded very clearly. The famous Yenangyoung field in Burma is an elongated dome of great extent, nearly symmetrical, and only slightly affected by purely local faults. It is isolated from any other flexure by miles of approximately horizontal strata, and thus drains a large area, while steep dips occur on either flank, ensuring a high concentration of the petroleum. About two square miles of available drilling area is provided on its crest. It is obvious that under such conditions hydrostatic pressure of water in the strata is enabled to concentrate the petroleum from all sides towards the summit. In such ideal structures, whatever be the quality of the oil, and however small the porosity of the oil-bearing strata, such a concentration is bound to take place and large productions may be expected whenever the oilsands attain to a reasonable thickness.

Symmetrical Anticlines.—Next in importance comes the simple symmetrical anticline (cp. Plate VIII), either without pitches of the axial line, or with pitches too low to have affected the structure favourably or unfavourably. Many of the Eastern fields in the United States have structures of this nature, the anticlines, though extensive, being often so low and flat as to be only distinguishable by very careful levelling or by evidence from actual bores. It is obvious that the greater the extent of the flexure, the greater should be the concentration of oil towards the crest, given sufficient hydrostatic pressure. The effects of pitches and gentle dips will depend to a great extent on the nature of the oil and the porosity of the oil-bearing strata; the greater the specific gravity of the oil and the smaller the porosity, the slower and less complete will be the migratory movement. Thus structures that have proved remarkably favourable for the production of a light oil of paraffin base, may not cause any great

concentration of a heavier grade of petroleum. In the United States the fields of New York, Ohio, Pennsylvania and Virginia, where as a rule the oil is light and mobile, show many instances of very flat structures, anticlines with slopes of twelve feet in a mile, for instance. It was in these fields that drilling for oil was first attempted and learnt, and they were taken as the type of what oilfields should be. This idea still survives to some extent in spite of the discovery of so many great fields with totally different structures. The advantages of these eastern fields in the States are many; horizontal or low dips make the easiest drilling, and the strata being palæozoic are mostly fairly hard and not very liable to "caving," so that drillers trained in these fields were acquainted with few of the difficulties attendant on drilling in soft Tertiary strata. When oil began to be discovered in other provinces under entirely different conditions, many a field that has since proved very profitable was condemned at first because it did not conform to the structural peculiarities deemed essential in the fields of the Eastern States, and many a practical operative, with only experience of the Eastern fields, proved a failure when confronted with the task of drilling through soft and steeply dipping Tertiary strata.

Asymmetrical Anticlines.—Another form of structure that has provided many excellent fields is the asymmetrical anticline. This is an anticline with one flank gently and the other steeply inclined; the latter in some cases may be vertical or even inverted. Such flexures usually occur nearer to the central axis of folding than symmetrical flexures. The "terrace structure," well known and much sought after in the eastern fields of the United States, may be regarded as a special case of this form of structure, an anticline so flat and gentle that the gently dipping flank is for all practical purposes horizontal. In sharp asymmetrical anticlines such as those at Kasr-i-Cherin in Persia, and Yenankyat and Singu in Burma, it is evident that drilling on the actual line of crest is useless; the drill soon enters steeply dipping beds where great difficulties may be encountered in the drilling, while there may be no possibility of penetrating to a sufficiently low horizon. Mr. G. B. Reynolds pointed this out in the Persian fields, and Mr. Pascoe in the Records of the Geological Survey of India has since explained the effect of such a structure in the case of the Yenankyat field

in Burma. This point will be referred to later in the chapter on "Location of Wells."

Compound Anticlines.—Compound anticlines may next be considered. These are only observed where the flexuring movement has been severe, and has produced a series of sharp folds, possibly with very steep flanks. The most striking instance that has come under the writer's observation is at Maidan-i-Naphtun, in Persia, where a group of no less than seven sharp local flexures is included in an area approximately one mile in breadth. Some of the flexures are so sharp that when a band of hard limestone is exposed on the crest it is possible to sit astride on the anticline. Highly inclined strata are the rule throughout this field, and vertical or inverted limbs of folds are common. These seven flexures converge towards and pass into one broader fold, which, being formed of strata less amenable to distortion, is somewhat gentler, and which really gives the key to the structure of the neighbourhood. The whole area is broadly anticlinal, and the sharp folds are merely puckers upon a well-defined flexure on a larger scale. Every well drilled in the area, whether upon one of the minor anticlines or in one of the synclines, has struck oil in paying quantity, but the surface indications of oil are nearly all upon or close to the crests of the minor flexures. These minor folds, though very striking and impressive, can therefore be disregarded and the compound anticline considered as a whole.

Synclines.—Mr. W. T. Griswold has pointed out that under certain conditions synclines may be exploited for oil successfully. The necessary conditions are that the strata are not waterlogged, and are so covered or sealed that water cannot enter the oil-bearing bands at outcrop. In such circumstances any petroleum in a porous rock will tend to collect at the bottom of the syncline under the force of gravity. It is very doubtful whether many such cases exist, though, in rainless regions or where the bulk of the strata are practically impervious to water, such conditions are possible.

With an oil of approximately the same specific gravity as water, displacement by the water might be very slow and never quite complete: so a certain quantity of the petroleum might remain in synclines, especially if deposits of asphalt were formed upon the outcrops by inspissation of the exuding

petroleum and the downward percolation of water checked if not entirely prevented. Thus, although with a light oil it may very seldom be worth while to drill in a syncline, with heavy asphaltic oils and in regions where rainfall is very small, shallow synclines might be worthy of being tested, and might prove highly productive. Even in Trinidad where the rainfall is high there is some evidence in favour of making a test of one of the shallow synclines, where extensive asphalt deposits cover most of the outcrops of oil-bearing sand. Where oils are very heavy and sluggish, a certain proportion of water in the oilrocks is rather a benefit than otherwise, assisting the flow of oil.

Monoclines.—Finally, oil may be obtained from monoclines, often in great quantity. In such cases the more gentle the dip, the better, but even quite steeply inclined strata may yield good productions. Many of the great oilwells in Russia are drilled into strata which crop out at the surface at no great distance: the new and much boomed field of Maikop is shown by the published geological maps to be in a outcropping series. In Peru, Trinidad, and some parts of California and Mexico, good productions have been obtained from beds that crop out in monoclines. It is to be noted that in these cases the oil is asphaltic and of fairly high specific gravity, the latter quality being due, partially at least, to inspissation.

In Burma, where a light oil of paraffin base is the characteristic petroleum, no adequate production has ever been obtained by drilling in a monocline to strike an outcropping oilsand. Native hand-dug wells have occasionally been worked at a profit for a short time in such structures, and many trial bores have been made at great expense, but all have been abandoned finally as unprofitable propositions. Except where the strata are for the most part impervious, and there is a probability of striking some isolated lenticular bed of oilrock, there is little hope of obtaining paying productions of light mobile oil by drilling in a monocline where all the horizons crop out. Thus, the class of oil to be obtained must be considered in relation to the structure; conditions favourable for an asphaltic oil may be quite unfavourable for a light paraffin oil.

It must not be forgotten in dealing with a monocline that it is really part of a great curve, on the flank of either some great anticline or syncline. Dips do not continue far at the same angle when traced downwards, as the geologist will discover

at once in plotting sections. Any sudden change in angle of dip may have great effect on production. Thus, though a well may begin in strata dipping at 45 degrees or more, by the time the oil-bearing rocks are reached the dip may have decreased to 20 degrees or less, or may have increased and even become vertical. Each case must be worked out from the geological map of the area, for it is generally quite absurd to calculate on a dip remaining constant for any considerable distance. Before any wells had been commenced in an area now being exploited by a company in Trinidad, the writer (then Government Geologist in that colony) worked out the vertical and lateral changes of dip, where direct evidence of the inclination of the beds was very scanty and often unreliable, and furnished those responsible for the exploitation of the ground with particulars of the depth to the observed oil-bearing bands in different places and the angles of dip at which each would be struck, particulars which in the end were proved to come within a very small fractional error of the actual results obtained. In this case projection of the observed dips from the nearest reliable section would have given an entirely erroneous result, and would have made the area appear very unfavourable for development work. Every bit of evidence bearing upon change of dip must therefore be noted, and when outcrops can be traced, even though no actual observation of dip can be made, it is often possible to estimate change of dip by measuring the distances between two known outcrops. The writer has often found this method of great service in obscure ground.

Where the dip in a monocline suddenly becomes shallower, or where a sudden change of strike occurs, especially where a bend in the strike concave to the direction of dip in the monocline is observed, there is nearly always some favourable effect upon the concentration of petroleum. The oil nearly always is found to have migrated towards such structures. This can be readily understood in the case of a bay or bend in the strike which is frequently accompanied by a lowering of the dip; it is in fact an abortive anticline, since a tilting back of the monocline to a position of horizontality would make an anticline or dome of such a structure. Instances of this may be studied in Trinidad, perhaps the most remarkable being at Pala Seco near the southern coast on the northern flank of the

great southern anticline. Structures such as this may be due to movements earlier than that responsible for the monocline, and the concentration of petroleum may have taken place prior to the great movement which caused the main flexures of the country. However this may be, such structures, bays in the strike concave to the direction of dip, always favour migration and concentration of oil.

Every structure produced by folding can be classed under one or other of the heads detailed above.

Faulting.—Faulted areas are not to be regarded as a special class of structure, but faults may be of great importance structurally, so that it is necessary to give some account of how they occur in oilfields and what effects may be attributed to them.

The flank of any fold may be replaced by a fault, partially or wholly; in this case it is a strike dislocation having the same effect as a very sharp unbroken fold would have, and obviously due to the same movement that flexured the strata. In many cases what is mapped as a fault at the surface may become a sharp flexure at some distance beneath, where the load must have been greater during the period of movement, and consequently a higher coefficient of elasticity of the strata can be postulated. This applies both to "normal" and "reversed" faults, the former being in evidence on the flanks of symmetrical or gentle flexures, while the latter are frequent on the steeper side of asymmetrical folds especially where vertical or inverted strata are observed.

In areas under insufficient load the cohesion of the strata may be overcome under flexuring stresses, and faults may be developed in many directions, all, however, having some relation to the flexure that the stresses are tending to form. Indeed, it is only under such conditions that what is called, rather unfortunately, a "normal" fault can be produced at all. The "normal fault" of the textbooks, a dislocation with a vertical or nearly vertical displacement, the downthrow being in the direction of hade, is by no means a common phenomenon in nature; it is only under simple conditions that such dislocations are physically possible.

A dislocation must begin somewhere and must die out somewhere, so it can be regarded as a sag or tilt, and strike faults whether normal or reversed, whether thrusts, "slides," or the doubtfully possible "lags" of some authors, are direct

and inevitable special phases or flexuring movements. Dip faults on the other hand may be simple tilts or sags, or may have a greater or less horizontal component. Many dip faults which map as normal faults, and are considered as such, can be proved to be largely horizontal displacements, thus approximating to the nature of "wrench faults." Every fault must be considered in relation to the flexuring movement, and thus the observation of a fault should be a help rather than a hindrance to the elucidation of structure, since, when once the direction of throw has been determined, it shows at a glance what tendencies of movement were induced in the strata in that particular locality by the stresses to which they were subjected. A *map* may be complicated by faults, but the *structure* should be explained by them rather than rendered more difficult to understand. The geologist who, after describing the structure of an area, concludes by saying that "there seems to be a good deal of faulting," or who tries to safeguard his views of a structure by saying "there may be a fault," which, if present, will put a different construction on the evidence, admits by so doing that he has not mapped the area, and has only the vaguest general idea of its geological structure.

Of course in strata of Palæozoic or Mesozoic age faults may be very numerous and of many different ages, but we are dealing principally with Tertiary rocks where the flexuring and faulting are usually simple, and the stresses that caused them easily understood. Petroleum is very seldom, if ever, found in highly faulted and contorted strata of Palœozoic age.

Since faults and folds are parts of the same earth-movement, the effects of faults upon an oilfield need not necessarily be prejudicial; strike faults may indeed help to ensure a greater concentration of the petroleum towards the crest of a flexure, and dip faults in a series where there are many oilsands may bring about communication between different sands, and so have a notable local effect upon production. Where the bulk of the strata are impervious, an oilsand which would otherwise crop out at the surface may be cut off by a fault and sealed beneath impervious beds (Fig. 2), and thus yield oil under much higher pressure when pierced by the drill than if it cropped out in the vicinity.

To illustrate the interdependence of folding and faulting,

and at the same time the effects of two folding movements in different directions, we may take the Yedwet inlier in the Magwe district of Upper Burma. This was the first area

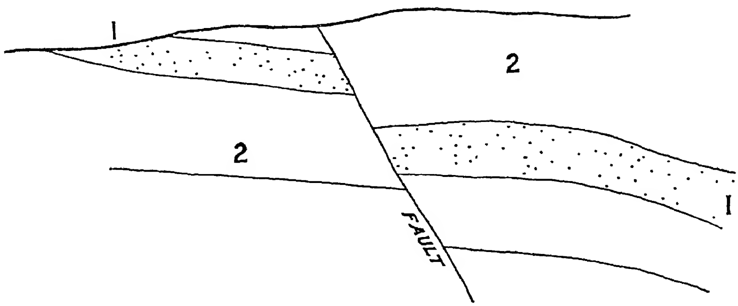

FIG. 2.—Fault sealing up an oil-rush. 1. Oilrock; 2. Impervious strata.

examined by the writer in Burma, and it proved a very fortunate one on account of the importance of the evidence obtained.

The area consists of an inlier of the Pegu Series, surrounded by, and in places capped by outliers of, the unconformable fluviatile Irrawaddy Series. The inlier has an oval outline, and dips are gentle throughout, seldom rising to more than 20 degrees, and that only towards the margins. Presumably, then, the structure was dome-like. Careful examination proved that there was evidence of two flexuring movements, both very gentle, one tending to produce flexures running E. 20 degrees N. to W. 20 degrees S., of which two were recognized in the area, and another tending to produce flexures running almost north and south. The general form of the inlier is due to this latter movement, which was easily identified with the main flexuring movement of Burma. The presumption was that the former movement was an earlier one, which had not been recognized previously in Burma.

The flexures are so gentle that a very simple case of the dynamic conditions produced by one movement on the results of an earlier one is presented. The strata had evidently not been under great load at the time of the last movement, as a number of small faults were detected in various parts of the area. These faults are of the same age, they run into each other, and no fault displaces another. They have therefore

evidently been caused by the same movement. There are two main directions for the faults, and though there are local modifications and variations, the lines along which dislocation has taken place are wonderfully constant throughout the area, viz. E. 20 degrees N. to W. 20 degrees S. and roughly north and south. That is to say, the systems of faults are parallel to the strike-lines produced by the two movements.

The process which caused these faults can be expressed very simply by a diagram (Fig. 3). Assuming that the movement

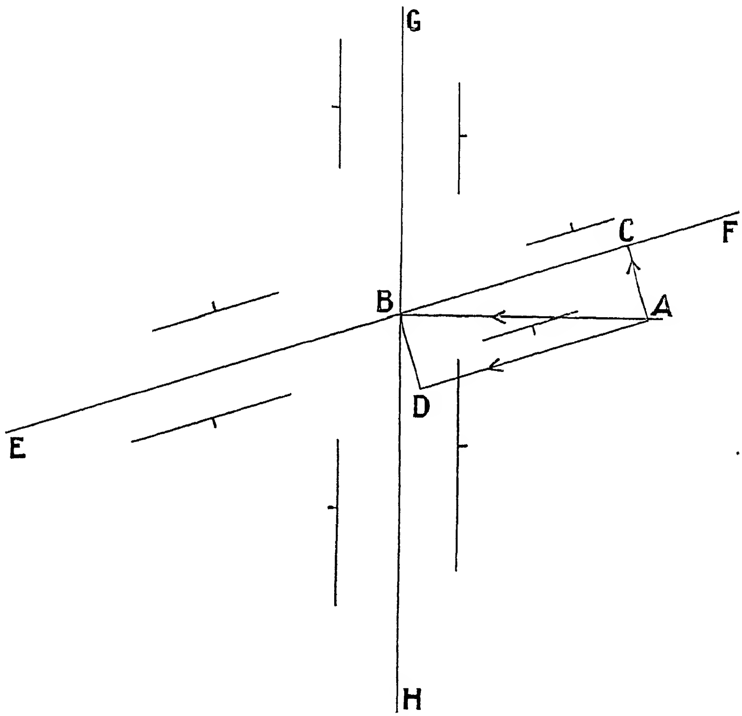

FIG. 3.—E F = crest of earlier flexure; G H = crest of later flexure; ⊢ = faults showing down-throw.

producing the two flexures running E. 20 degrees N. to W. 20 degrees S. is the earlier, we have a force AB, impinging obliquely upon a flexure EF. The force will be resolved into two components AC and AD, one tending to increase the height of the fold and the other tending to compress it and to raise a flexure in the direction BD. It is a simple parallelogram of forces. Let

us consider how different parts of the area will be affected. A point upon the crest of one of the cross flexures will tend to rise, especially where the effects of both movements coincide. On the other hand a point in the syncline between the two cross flexures will be affected differently according to its position with regard to the second movement. Towards the margins of the area a point in these synclines will tend to sink, towards the centre of the area one component will tend to make it rise and another to make it sink. The strata in such localities will be under a peculiar condition of stress, and adjustment will be arrived at by the developments of small faults. Thus we get, so to speak, strike faults of both movements, though produced simultaneously and the directions of throw will be as shown in the diagram. All these faults were noted and mapped before any theoretical ideas as to their origin were conceived. Replacing the faults by folds the action is quite easily intelligible, and can be reproduced experimentally.

The evidence obtained from this area was applied to other fields in Burma, and served to explain the presence of faults in many localities where physical reasons for their origin had not been ascertained. One of the first results was the proof of the relative ages of the two movements; that responsible for the cross flexures was found not to affect the younger Irrawaddy Series, while the other movement throws it into great folds. The cross movement is therefore the earlier.

The formation of dome structures, which are common in inliers of the Pegu Series, was also accounted for. It is almost entirely due to elevation by the earlier movement which, though always gentle, has had the effect of raising parts of the series locally before the commencement of the great movement which has produced the main strike-lines of the country.

Another interesting point is that petroleum has never been obtained in paying quantity in any field that does not show some traces of the earlier movement, even though these traces are often almost obliterated by the much more powerful later movement. It would seem that there has been a preliminary concentration of the petroleum contents of the strata towards the earlier flexures, which concentration has been greatly increased afterwards by the later and greater flexuring.

It is, of course, only in simple cases that such conclusive results can be obtained with certainty, but the Yedwet inlier

will serve as an example of how the evidence from one area may assist in elucidating the more complex structures of other areas, and of the necessity for considering flexures and faults together and not separately.

Unconformabilities.—The only other phenomena of importance that must be considered when dealing with the geological structure of a country are those associated with unconformabilities. Unconformable junctions of different series, or of different parts of the same series, may often be the cause of considerable difficulty in the working out of the structure of an oil-bearing territory. Among Palæozoic or Mesozoic rocks there may be no difficulty in recognizing an unconformity, but in soft or lightly compacted Tertiary strata the discordance may never be seen in actual section, while the rocks both above and below may have very similar lithological characters, and fossil evidence may be wanting or too scanty and too little known to be conclusive. In such cases there is a danger of an unconformability being unnoticed, with disastrous results when estimates of thickness of strata and depth to oil-bearing horizons are being calculated.

When proved, however, by careful mapping, an unconformability may be of very great assistance to the field student in giving evidence as to the age and nature of the earth-movements in the country that is being examined. A case has just been quoted from Burma, where the proof of the relative ages of two movements depended on the evidence from strata of two different series, separated by an unconformability. Had the unconformability between the Pegu and Irrawaddy Series not been ascertained, this valuable evidence would have been lost. The discordance between these two series, moreover, is sometimes not easily recognized, the junction has several times been described as a passage, and at one time the Geological Survey of India were actually mapping one of the locally basal beds of the Irrawaddy Series as the topmost bed of the Pegu Series.

The recognition, therefore, of an unconformity becomes a matter of very great importance, and it must be distinguished from a plane of merely local or contemporaneous erosion. Local erosion is very frequent among rapidly accumulated Tertiary strata, such as are characteristic of areas where deltaic conditions occurred on a large scale. At the base of every thick or coarse-grained arenaceous group, where it rests upon

finer argillaceous sediment, there are nearly always some signs of erosion of the underlying strata, and the divergence in strike and dip of the arenaceous group if current-bedded may be considerable, so that in a small section the appearance of a well-marked unconformity may be presented. On the other hand a great unconformability, representing a gap in the geological record, may appear in small sections to be a perfectly conformable sequence.

Careful mapping on a large scale will always make certain of any unconformability of importance by disclosing the overlap of one series on the other, but where evidence is very scanty, or when there is not sufficient time available for detailed work, other methods must be relied on.

The presence of some mineral or minerals or fragments of rock in one series and not in the other is a bit of evidence to be noted at once, as it points to the strata having been formed from the denudation of different rocks, so that if any such sudden change in mineralogical composition is detected and proved to hold good over any considerable distance and through thick masses of strata, a *primâ facie* case for the presence of an unconformability has been made out.

Differences in the state of mineralization of the strata are also to be noted, the bedding, lamination and jointing may be of different characters in two apparently conformable series, and finally, and most important of all, the lower series may show evidence of small folding or faulting movements that do not affect the upper series.

In the case of the unconformability between the Pegu and Irrawaddy Series in Upper Burma, the point was established beyond doubt by evidence obtained from an area far to the northward of where the question had first arisen and become of importance. The Irrawaddy Series was found some seventy miles to the northward to contain evidence of volcanic action several hundred feet above its base. This evidence included outflows of lava, and formation of explosion-craters with beds of ash and agglomerate. The ashes contained many blocks and fragments of metamorphic rocks, abundance of acid lava bombs and fragments including beautifully silicified rhyolites. The strata of the Irrawaddy Series above the volcanic beds were found to contain pebbles of metamorphic rocks and agate, and occasionally much decomposed felspar and kaolin.

The basal beds of the Irrawaddy Series in the Magwe District to the southward, where the unconformability was in question, contain well-rolled pebbles of metamorphic rock and agate (from the silicified rhyolites), while kaolin was found in some of the sands. None of these appear in the underlying Pegu Series, and it was the occurrence of kaolin in a bed, then considered to belong to the Pegu Series, that first turned the attention of the writer to the possibility of there being an unconformability. Examination of intervening, but discontinuous, areas, gave confirmatory evidence, and it became clear that the basal beds of the Irrawaddy Series, in the Magwe District are post-volcanic, and that the pre-volcanic beds of the Irrawaddy Series, some hundreds of feet thick in the Pakokku District, have either never been deposited in the Magwe District or have been removed by denudation. Thus a considerable gap in the succession was proved, and the detection of pre-Irrawaddy movements, as explained above, completed the chain of evidence. The identification of fossil horizons in the Pegu Series has since made clear that this unconformability is often of very great extent, and that great thicknesses of the upper beds of the Pegu Series have been removed by denudation in many localities before the deposition of the basal beds of the Irrawaddy Series.

Another instance of unconformability, for long a matter of doubt, may be given from Burma, namely, the unconformability between the basal beds of the Pegu Series and the underlying Bassein Series, probably of Eocene-Cretaceous age. This line of discordance had been crossed and recrossed by several geologists without its being detected, and presumably they classed the underlying Bassein Series with the petroliferous Pegu Series above. The first evidence that called attention to the possibility of there being an unconformity was afforded by the fact that the great littoral arenaceous group of the Yaw sandstones, which forms a very strong feature in the foothills of the Arakan Yomas, is underlaid by softer strata with a rather different aspect as regards lamination, bedding, jointing and state of mineralization. Subsequently evidence of movement, folds, and small faults, were noted in the underlying series and proved not to affect the Yaw sandstones, and finally the mapping on the six-inch scale of a few square miles, where excellent sections can be seen, proved that the Yaw

sand-stones transgress over hundreds of feet of the Bassein Series. In many small sections, notwithstanding, the two series differ so slightly in strike and dip as to appear perfectly conformable.

In Persia the detection of an unconformability proved of the greatest importance from the practical point of view of oil-field development. During the detailed mapping of the oilfield at Maidan-i-Naphtun the possibility of there being such an unconformability had been suggested by the discovery of the detrital limestones and breccias, and the occurrence of great conglomerates at various horizons in the Tertiary series full of well-rounded pebbles of limestone. It was known from the work of previous observers that a great mass of limestone (the Asmari limestone) lay at a lower horizon, and it had been suggested that drilling in anticlines of this limestone might be profitable. When the Asmari limestone was first encountered by the writer on the north-west pitching end of the Asmari anticline, evidence of unconformity was at once searched for, but beyond thin beds of detrital limestone resting here and there on a somewhat irregular surface of the calcareous rock, the occurrence of one small patch of breccia, and a slight discordance in dip and strike between overlying beds of gypsum and the Asmari limestone, no evidence was forthcoming. The various kinds of limestone preserved in pebbles and fragments in the conglomerates and breccias near Maidad-i-Naphtun were, however, matched from the solid outcrop of Asmari.

A few days later, in the next great anticline to the north-eastward, where the Asmari limestone again appears, demonstrative evidence at once came to light. A great transgression of beds high up in the oil-bearing series, chiefly conglomerates full of limestone pebbles, was observed cutting right across the anticline of limestone, which in places is entirely removed by denudation, some 2000 feet of thickness having been denuded. On the flanks of the limestone outcrop bed after bed of the oil-bearing series makes its appearance between the calcareous rock and the great conglomerates which lie across the denuded anticline.

Subsequent field-work proved that these anticlines were denuded as they rose under the flexuring movement, and that the succession may be entirely conformable in the synclines; consequently at the north-west end of Asmari Hill,

where the fold of lime-stone pitches sharply downwards, no striking evidence of unconformity could be expected.

The point of importance from the oil-development point of view is that the oil-bearing strata belong to a different series, and are of later age than the Asmari limestone, and to attempt drilling in the latter would be entirely speculative and unjustifiable. But for the detection of this unconformability we should be, as far as that region in Persia is concerned, still in the dark as regards the conditions under which these Tertiary strata were deposited, and as to what districts are most favourable for exploitation.

In southern Ohio probable unconformities that do not crop out at the surface have been detected in strata either horizontal or very gently dipping, and the transgression is sometimes exceedingly regular. Mr. Frederick G. Clapp has explained this matter very clearly in one district, showing that the Clifton sand (a well-known oil-bearing horizon) increases in depth eastward at a rate of from 30 to 100 feet per mile more than is indicated by the datum line given by a characteristic bed exposed on the surface. In such a case the evidence from wells becomes more important than a detailed study of the surface. But such remarkable regularity must be exceedingly rare, and there is always the possibility that the effect may be due to lateral variation, the thinning or thickening of the oilsands and the beds intervening between them and the surface, rather than to unconformability and overlap. Variations in thickness as great as this when a series is traced far in the same direction may be observed in the Sabe and Yenankyat fields in Burma, where a series of deep valleys across the strike make it possible to measure the thicknesses of groups in actual sections. In cases such as that of Southern Ohio the evidence from wells is essential, and it is a matter more for the consideration of the oil-engineer than for the geologist, whose examination of the evidence at the surface should be complete before wells are drilled in a new field.

Unconformabilities, the extent and directions of increase of which have not yet been worked out, are already causing difficulties to those entrusted with the exploitation of some areas in Trinidad, and have perhaps done something to confirm the popular idea that petroleum is a very capricious

mineral, and that, as the driller is fond of reiterating, "the only way to find oil is to drill a hole for it."

But of all oilfields the successful development of which depends on a study of unconformability and overlap, and the directions in which erosion of the denuded surfaces beneath unconformable junctions increase or decrease, the most remarkable is perhaps the island of Barbados. Here we have evidence of folding movements of considerable severity acting in different directions and at different times. There are two great unconformities. The oil-bearing series, much folded and not a little faulted, is overlaid unconformably by a series of oceanic deposits, which in their turn have been thrown into flexures, raised within the zone of denudation, and overlaid unconformably by a thick mass of coral limestone of comparatively recent date, which rises in terrace after terrace lying horizontally and covers by far the greater part of the island. The surface of the oil-bearing series is irregular, and there is an overlap of the upper beds of the Oceanic series over the lower, while there is another overlap of the coral limestone over the Oceanic series, which has doubtless been removed by denudation in many places, so that the coral limestone rests directly on the petroliferous series (the Scotland Beds) in several districts. Yet in spite of sharp folding, faulting and unconformabilities, oil has been produced in small quantities for several years, and though the work has not been a great commercial success up to date, there are prospects of valuable oilfields being proved. Success will depend upon the working out of the effects of the different movements and consequent unconformabilities, and the determination by such methods of where the petroliferous strata, whether deeply buried beneath younger deposits or not, will be found under conditions most favourable for good productions of oil.

Sufficient has been written to show that unconformabilities are common phenomena in Tertiary oilfields, and that they must be studied carefully if the structure of a country is to be ascertained beyond the possibility of doubt. They are of great practical importance to any company undertaking development work.

Thus folds, faults, and unconformabilities must be considered together and in detail before any connected history of a country or district can be presented, and it may often be

necessary to visit areas far beyond the confines of a district before some of the problems in structure that it exhibits can be solved. There must be no such thing as *opinion* about geological structure; only the facts will suffice, and the geologist must make absolutely sure of structure if the drilling programme is to be directed with the least possible number of failures and the greatest number of successful results, since in the area selected through knowledge of the oil-bearing series and its lateral variations it is the geological structure and nothing else that determines the extent of each field.

An oilfield with several producing wells, but with no geological map, may be part of a great potential producing area, or may be the merest fringe in which oil production is possible. The area between two producing wells is *not* developed or proved, unless the geological structure of the intervening ground is known, and known to be favourable. But a very few wells, carefully located, will enable the geologist to determine within reasonable limits the probable productive area of a field.

Hence every detail of dip, strike, change in dip or strike, hade of axes of flexures, and pitch of axial lines must be noted, and if the area be undulating the height of each locality where observations have been made about a datum line should be ascertained. Then and only then can absolute certainty as to structure be achieved.

CHAPTER VI

INDICATIONS OF PETROLEUM

Our Manager cables as follows:—"Borehole No. 3 has reached a depth of 792 feet, and the indications are favourable." To how many meetings of anxious shareholders have such or similar comforting words been read, and how often do we see a message of this nature dealing with a new field under exploitation quoted in the public press? And it would be a very bold and even impudent shareholder who would rise in his place and ask pointedly: "What are the indications, and why are they considered favourable?"

Such queries would no doubt receive answers, but in all probability they would be vague and carefully guarded statements, for the Chairman or Managing Director of a Company may very naturally consider that it is not his duty to study geological data; he depends upon the Manager or Field-Superintendent, who has cabled; or the log of the well has been submitted to an expert at home, who has pronounced the indications "favourable." And the shareholders may go away satisfied, though it may be that neither Field-Manager nor expert has any certain knowledge of what would be "favourable" indications *in the locality and at the depth stated.*

This at once raises the question of what are favourable indications of petroleum, *i.e.* indications that point to the probability of good productions being obtained.

The subject naturally divides itself into (1) Surface Indications, and (2) Indications in a borehole.

(1) **Surface Indications.**—It is to indications at the surface that attention has always been attracted. The expert who visits a new district goes first to the localities where "shows," as they are called, are to be seen, and it is largely by the presence of "shows" in any piece of land that it is judged

by persons without technical knowledge. The field-student will do well to make himself acquainted as soon as possible with the nature of the "shows" which he may expect to find in the country that he is examining. He has, let us say, made his preliminary traverses, gained some idea of the lateral variation, and discovered that favourable structures produced by the earth-movements he has been studying are to be found. The time now comes for him to study the indications at the surface as a guide to what thicknesses of strata and what horizons may be expected to prove petroliferous, and what variety of oil is present.

Let it be admitted at once that the actual shows of oil are of great importance, much is to be learnt from them; but the study of structure must take first place. It is a surface show that always attracts the lay mind. During the writer's first examination of an oilfield he inadvertently grieved an enterprising pioneer who had pointed out a small seepage with the remark "there is what would make glad the heart of a Rockefeller," by bluntly answering that he himself took little interest in such indications as long as the geological structure was still unsolved. As a matter of fact it is very frequently where surface shows of oil are seen that drilling would be entirely unsuccessful, and many of the greatest oilfields known to-day have not a single surface indication within their length and breadth.

Surface indications are of various kinds according to the class of oil, the nature of the strata, and the geological structure. They comprise:—

(*a*) Seepages of oil.
(*b*) Asphalt deposits.
(*c*) Evolution of gas from gas-pools, mud-volcanoes or dry ground.
(*d*) Outcrops of bituminous strata, and
(*e*) Veins of manjak or ozokerite.

In addition to these the evolution of hydrogen sulphide may be in some cases a favourable indication, and crystals of sulphur in cavities in a rock, or the presence of minute traces of sulphur in flecks and patches may also be important. Belts of stunted or sickly vegetation may give a valuable indication

where no solid evidence is available. Finally a faint odour of petroleum may sometimes be detected where no actual seepage can be discovered.

(*a*) *Seepages of Oil.*—Where an oilrock reaches the surface there is generally some sign of petroleum. It should be looked for in low ground, in the beds of streams, or at the foot of hills, and, if the strata be bent into anticlinal form, at or near the crest of the anticline. In many cases where the upper part of an outcrop has lost all signs of petroleum through weathering, a seepage will be noticed where the outcrop crosses the valley of some small stream or gully. In such localities films of oil with a beautiful iridescence may be seen on the surface of the water. The odour will at once distinguish these films from decomposing bicarbonate of iron which also gives an iridescent film (of hydroxide), and which has often been mistaken for evidence of petroleum. The films in these two cases, however, are by no means identical, and when seen side by side could never be mistaken.

If the seepage be more copious, brown or greenish or black drops of oil may be seen, and these may collect into patches on the water near their source or in eddies and still pools down stream. Gas is frequently seen bubbling up through the water. In some cases actual trickles of oil out of the rock may be observed. But the greater part of the outcrop of an oilrock will probably give no indication of being petroliferous until dug into for a few inches or perhaps feet.

The cavernous detrital limestones of Maidan-i-Naphtun exude oil rapidly in the valleys of streams, and where the water is clear small spherical drops of the oil may be seen emerging from cavities and rising to the surface. But the greater part of the outcrop is barren of indications. The greatest natural show of liquid petroleum which the writer has seen occurs in this field; as much as 20 barrels a day of oil flow to waste in one stream. Three or four brisk seepages combine to make up this quantity, and from time immemorial the Shusteris have collected the petroleum and burnt off the light oils to obtain bitumen.

Another remarkably large seepage occurs in the Trinity Hills Forest Reserve in Trinidad. At the time of the author's visit to this spot a stream some three yards in breadth was

covered entirely with a dark brown oil with green fluorescence for a distance of nearly a hundred yards, while gas bubbled up briskly both through the water and from several places on the banks. This show is on an outcrop of the Galeota Oil-bearing Group.

Oils with a paraffin base usually make smaller and less striking seepages than asphaltic oils, as the results of inspissation are more readily washed away by rains, and the rock from which the oil exudes is more easily and quickly robbed of its petroleum contents under weathering processes. Many of the outcrop shows in Burma, where the oil is generally light and full of solid paraffin, consist, even on the outcrops of thick oil-sands, of very small pools not more than a foot or two in diameter in the courses of small ravines and stream valleys.

Oil obtained from seepages is always more or less inspissated, and does not give a fair sample of what may be obtained by drilling, the light fractions having evaporated.

An asphaltic oil can usually be distinguished from a paraffin-base oil by the manner in which it inspissates; the former generally remains liquid or semi-liquid for a longer time but dries finally to black asphalt; the latter soon coagulates into little flakes often of a reddish brown colour, and when present in quantity and containing much solid paraffin dries into a soft mass like vaseline, which does not adhere to exterior objects with the same tenacity exhibited by asphaltic oil, and is consequently more easily washed away.

The most remarkable seepages of oil are those that have been naturally filtered, and partly or entirely decolorized. In such cases the petroleum, though it has probably lost its most volatile constituents by inspissation, has also been deprived of the bulk of its heavier fractions by filtration. The "white oil" of Kala Deribid in Persia has already been mentioned; it is a limpid mobile liquid that the writer could hardly believe to be oil till he had dipped his hand in it.

Another interesting example of a filtered oil, this time of asphaltic base, may be observed exuding from an outcrop of sandy clays in a small tributary of the Lizard River in the south-eastern corner of Trinidad. The locality has been called "Lizard Spring." The oil is dark brown with a green fluorescence, and it collects on the surface of the water in the stream bed. When the writer was encamped in the forests

near this spot a sample of the oil was skimmed by means of a leaf from the surface of the water, bottled, and taken into camp, where it was burnt that night in a small open lamp, hardly clogging the wick at all. An analysis of the oil collected in this manner at Lizard Spring was made some years ago by Professor Carmody, Government Analyst of Trinidad, who found it distilled like a refined oil, and gave:—

Petroleum spirit	0
Illuminating oil	73
Lubricating oil	25
Residual bitumen	2
	100

The specific gravity was ·867, and the flash point was above 145 degrees (Abel's test). This oil is sufficiently inspissated to make it a perfectly safe burning oil, and to contain a fair percentage of heavy oil and residue. A year or two later a small excavation was made in the outcrop, at the author's suggestion, to obtain a fresher sample of the oil. Professor Carmody's analysis showed this second sample to contain:—

Petroleum spirit	12
Illuminating oil	81·25
Lubricating oil	6
Residual bitumen	0·75
	100

The specific gravity was considerably lower. This is obviously a dangerous oil on account of its percentage of petroleum spirit, and could not be burnt with safety in a lamp. The two analyses are interesting as showing the effects of inspissation. The oils are both well filtered by passage through the argillaceous strata, and it is hardly necessary to say that were a borehole drilled at this spot an oil of this class would not be obtained in any quantity, though heavier unfiltered oils from the same source would probably be struck.

Evolution of oil is not unfreqently observed in the sea, where an oil-bearing stratum is exposed beneath the water. In the Caspian Sea such shows were well known for many years before any active drilling was undertaken at Baku.

Off the coast of Trinidad there are many places where oil is occasionally to be seen. Perhaps the best known is just west

of the famous Pitch Lake, where a brisk evolution of gas with drops of brown oil may be observed about a quarter of a mile off shore. The activity of this show varies considerably, but on a breezy day the locality can usually be detected by the presence of a patch of smooth water, the film of oil covering it being sufficient to prevent waves from breaking.

At the mouth of the Vance River, and again at Point Ligoure, where outcrops of the Rio Blanco Oil-bearing Group run out to sea, the water is sometimes covered with a film of oil for a considerable distance. Other submarine shows near the eastern and south-eastern coasts are sporadic and occasionally of explosive violence; after an outburst sticky oil and soft asphalt are washed up on the shore in considerable quantity.

Off the south-western corner of Tobago there is apparently a submarine outcrop of oilrock, for sticky inspissated petroleum is washed up on the beach and the coral limestone in great quantity at some periods of the year.

(*b*) *Asphalt Deposits.*—Oils of asphaltic base nearly always make their presence obvious, when the conditions are favourable, by more or less extensive deposits of asphalt along the outcrops of the petroliferous strata. There is, of course, no hard-and-fast line between a seepage of crude oil and a deposit of asphalt; every gradation of sticky and inspissating oil between the two may be observed on the same outcrop. In Trinidad, where most, though not all, of the oils are asphaltic, the phenomena of asphalt deposits can be studied on a remarkable scale. Foremost of all comes the famous Pitch Lake, the best known, though not the most extensive, asphalt deposit in the world. Much has been written about it, and many theories have been propounded to account for the origin of this lake. Without going in detail through the theories of various authors and pointing out where each has advanced the knowledge of the day, it may be as well to give a brief description of the field evidence and the last published, and so far accepted, theory; the author may be pardoned for inserting a lengthy quotation from his official account from the Council Papers of Trinidad, No. 60 of 1907, more particularly as this account has been drawn upon extensively by others, and large portions of it published verbatim and without acknowledgment.

"A brief account of the evidence obtained in the field, and from other sources, must be given. The Pitch Lake lies upon

a well-defined plateau 138 feet above sea level. The area has recently been affected by gradual upheaval, as proved by raised beaches in the neighbourhood, and it is probable that the plateau at no distant date, geologically speaking, stood at or below sea level, and is in fact a raised beach or coastal beach itself.

The geological structure is a gentle anticline which runs roughly east and west, the lake being upon the crest. The vicinity of the lake is almost entirely covered with surface deposits concealing the solid evidence. The underlying rocks are lightly compacted and are often disintegrated to a great depth, and the surface wash of disintegrated material covers almost all the ground. The "brown shales" mentioned by Messrs. Louis and Gordon, though often giving an appearance of stratification, are not Tertiary sediments, but recent surface deposits. The brown colour is due to the presence of finely divided bitumen or asphalt dust.

The La Brea oilsand, a deposit of variable thickness, is the source of all the pitch. It crops out to westward of the lake in the coast section, to eastward of the plateau, and also to the southward near the Vessiny River, and in inliers in hollows. Its outcrop has been mapped for several miles. This oilrock is covered by a fine bluish clay, which, when impregnated sufficiently with bituminous material, has occasionally become ignited and burnt to porcellanite, *e.g.* south and south-west of the lake. The clay in its turn is covered by a soft yellow sand, the disintegrated outcrop of which covers much of the area north of the lake.

Wherever the capping of clay is thin, or the oilrock is merely covered by superficial deposit, or is actually exposed, soft asphalt exudes, forming small cones, examples of which may be seen beside the road between the Asphalt Company's works and the lake, and at several places north and west of the lake.

The oilrock, where it is exposed on the shore west of the lake, is a fine dark sand, so full of bitumen that the superficial layers actually flow slowly, the semi-liquid asphalt as it exudes carrying the inorganic material of the rock with it. Pieces of this rock may be twisted off in the fingers and rolled into pellets. An analysis of a specimen by the Government Analyst gives the following results :—

Water, etc., volatile at 100° C.	5·24
Bitumen	15·1
Non-bituminous organic matter	29·70
Ash	49·96
	100·00
Soluble in petroleum ether	8 per cent.

This specimen was taken from a weathered tide-washed outcrop. The quantity of non-bituminous organic matter is remarkable, but, as will be seen later, recent work by Mr. Clifford Richardson has thrown much light upon this point.

A shallow boring (about 60 feet) was made in the outcrop of oilrock west of the lake, many years ago. It is situated 200 feet from the sea and yields a small quantity of rather heavy oil. A sample taken from the surface gave the following results on analysis by the Government Analyst:—

Specific gravity	0·950	
Mineral matter	0·02	per cent.
On distillation—		
Water	1·2	
Petroleum spirit	12·8	
Illuminating oil (150° – 300° C.)	36·0	
Lubricating oil (above 300° C.)	32·0	
Residual bitumen	12·3	
Loss	5·7	
	100·0	

In the sea at a distance of about 200 yards west south-west of the last-mentioned locality, there is an oilspring. A smooth patch on the water is often conspicuous, and in it drops of brown oil may be seen floating, while gas bubbles up all round, and a film of oil sufficient to prevent waves from breaking sometimes covers the surface for a considerable distance.

In the hollow east of the plateau on which the lake is situated, the oilrock crops out again, and large flattened cones of semi-liquid asphalt may be seen with slight evolution of gas. In these cones or rather pools of soft pitch the material can be seen exuding, and it is streaky with the quantity of inorganic matter brought up with the bitumen, indicating that either the cohesion of the oilrock breaks down when it is exposed, or that superincumbent material is carried up by the flow of asphalt and gradually absorbed in it.

Borings made by the Asphalt Company in 1893 have furnished additional evidence of the underlying oilrock. In the centre of the lake a depth of 135 feet was reached without touching bottom, but at 1000 feet from the centre on the north side fine sand was struck at 80 feet, then more asphalt, and at 90 feet asphaltic sand, *i.e.* the more or less disintegrated oilrock. A boring south of the lake also struck a hard asphaltic sand, obviously the same which crops out to the east-south-east, the course of which can be traced by lines of asphalt cones. The oilrock cannot be identified in the coast section in Guapo Bay, but porcellanite and lignitic shales covered by sands and sandy clays probably represent it, and indicate that the oilrock is thinning out and the oil-producing conditions at this horizon ceasing in this direction.

The next evidence to be considered is the composition of the lake pitch. This is treated of so fully in Mr. Clifford Richardson's book, "The Modern Asphalt Pavement," that a few brief quotations will suffice. The average composition of the lake pitch is given as:—

Water and gas	29	per cent.
Organic matter, not bitumen	7	
Mineral matter	25	
Bitumen	39	
	100	

The asphalt is an "emulsion" of these constituents. The inorganic matter consists of fine sand and clay with a small quantity of iron oxide and soluble salts. Mr. Clifford Richardson gives an analysis of the mineral matter as follows:—

SiO_2	70·64
Al_2O_3	17·04
Fe_2O_3	7·62
CaO	0·70
MgO	0·90
Na_2O	1·56
K_2O	0·35
SO_3	0·97
Cl	0·22
	100·0

This corresponds with the composition of a normal sandstone, with slight admixture of argillaceous material. The microphotograph of the mineral matter which Mr. Clifford Richardson published ("The Modern Asphalt Pavement," p. 34) shows all the characteristics of the debris from an ordinary fine waterborne sandstone, the grains not being greatly abraded as in windblown sands, nor having any of the characteristics of silica deposited from solution. The finest material is a fairly pure clay. The percentage of "Organic matter not bitumen" presents a point of great interest; as recorded above, the percentage of this in the La Brea oilsand was as much as 29, while in the Rio Blanco oilsand it was only 0·46, a difference great enough to enable these different types of oilrock to be distinguished easily. Recent work by Mr. Clifford Richardson upon the absorptive properties of fine clays for bitumen explains the occurrence of this percentage of hitherto little-understood constituent in asphalts, oilrocks and manjaks. In a paper read before the American Society for Testing Materials, and afterwards published in the "Engineering Record," he describes experiments made with Trinidad lake-asphalt and tests of the absorptive and "adsorptive" properties of various fine clays upon solutions of bitumen. The results arrived at are briefly that fine clays have the power of decolorizing bituminous solutions by absorbing or "adsorbing" a proportion of the bitumen in such a manner that it cannot again be removed by the action of solvents. Thus the greater part of the "organic matter not bitumen" can be proved to be bitumen which cannot be removed in solution. The presence of water may also have some effect in favouring this absorption, but the proportion of fine clay present seems to be the more important factor. Applying these results to lake-pitch and the oilrock from which it is derived, we have at once an explanation of the presence of argillaceous material in the asphalt, and we must increase the percentage of bitumen in lake-pitch by almost, if not quite, 7 per cent. and the percentage in the oilrock probably by a much greater amount. This makes the breaking down of the cohesion of the oilrock on exposure much more intelligible.

The lake itself is, by the latest survey made under the supervision of the Inspector of Mines, 137 acres in extent, the margins being covered in places by superficial deposits washed

down from the surrounding ground. In the centre the surface of the asphalt is about six inches higher than near the sides, and for some distance from the centre there are no water-channels. Then comes a broad zone characterized by water-channels dividing the surface into roughly circular areas with rounded edges. Near the shore the pitch is harder as a rule, and less cut up by water-channels. Near the centre there is an area of very soft asphalt, where a little gas issues slowly, while there are similar but much smaller patches near the western margin and between it and the centre. The distribution of these areas of very soft pitch indicates the proximity to the parent oilrock, whence continuous but minute exudation of pitch is still taking place. Lest there should be any misunderstanding upon this point, it must be repeated that Messrs. Louis and Gordon have proved conclusively that the lake is exhaustible, and is being depleted at a very rapid rate, but the presence of the patches of soft asphalt, and the difference in level between the centre and sides makes it clear that additions of asphalt, probably amounting to only a few tons in the year, are still being made, just as the same material is exuding in the ground to the eastward and south-eastward of the lake.

The gas given off from the lake is chiefly sulphuretted hydrogen formed by the action of water on sulphur compounds in the asphalt. It is seen bubbling up in the water-channels. A small quantity of oil-gas, however, may be detected issuing from the soft patches.

The "pitch-lands" of La Brea village are undoubtedly, as pointed out by Messrs. Louis and Gordon, an overflow from the lake. This overflow has taken and occupied the valley of a small stream, known as the "pitch-lake ravine," and has in effect pushed the stream westward, where it now flows at a higher level than its original course. There is no evidence of any exudation of asphalt in the village lots, though gas has been detected issuing from the ground on one or two occasions. Weathered surface deposits underlie as well as overlie much of the land-asphalt, proving that the overflow, which has ceased some years ago, took place under subaerial conditions.

From the evidence detailed in the preceding pages the origin of the Pitch Lake can be explained as follows:—

In the first stage the La Brea oilsand, covered by its cover-clay and succeeding sediments, lay below sea-level. Under a

flexuring movement acting in a north and south direction, the area was subjected to elevation, a gentle east and west anticline being gradually formed, and the strata above the oilrock were raised within the zone of denudation, though probably still below sea level. Denudation of the crest of the anticline took place till the reduced thickness of the puddled cover-clay was not sufficiently tenacious to resist the upward pressure of gas

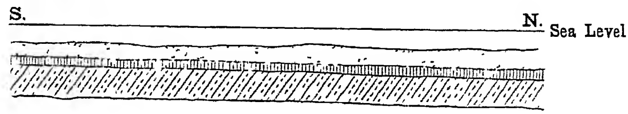

FIG. 4.—Stage I.

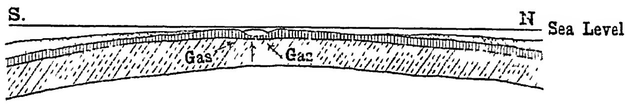

FIG. 5.—Stage II. Submarine mud-volcano.

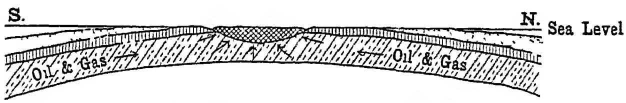

FIG. 6.—Stage III. Formation of plateau.

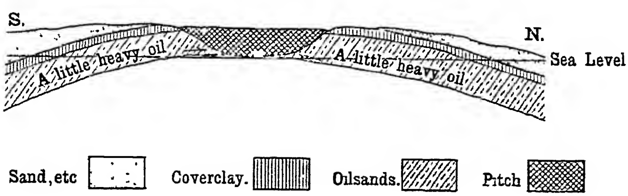

FIG. 7.—Stage IV. Present day.

FIGS. 4–7.—Diagrams to illustrate formation of Pitch Lake, Trinidad.

from the oilrock. A mud volcano would be the result, and, as denudation and elevation both continued, would increase in size. All this probably took place beneath the water. As the covering was gradually removed, oil began to exude and to dry up to a sticky asphalt.

About this time the anticline was probably becoming more clearly defined, and the site of the pitch-lake began to emerge from beneath the sea as a hollow in which discharge of gas

and oil was continually taking place, while mingling with inorganic minerals would be favoured by tides and wave action. This stage is marked by the formation of the plateau, suggesting that the surface remained at or near sea level for a considerable time.

As the land rose sub-aerial denudation would come into play, the oilrock itself being exposed over a roughly circular area defined by the extent of the mud volcano. The anticline being now well marked, gas and oil would be forced from all sides towards the crest, where the exposed oilrock would afford relief of pressure. The bituminous minerals being present in such quantities in the oilrock as to destroy the cohesion of the material on exposure, the solid rock would gradually crumble and flow into the cavity, while lighter oil and gas issuing from below assisted in the incorporation of the inspissating petroleum with the detritus of the oilrock and its cover-clay and all other material washed into the cavity. Thus the basin would be continually enlarged as fresh strata of oilrock were laid open to disintegration. Convection currents in the semi-liquid mass and discharge of gas, while there were still quantities of gas under pressure at deeper levels, would ensure a thorough mixing of the different materials into an emulsion. This action is still going on, but so slowly as to be practically negligible, while gas and light oils have decreased very greatly in quantity as the available supply of petroleum became inspissated.

Extrusion of semi-liquid bitumen proceeded to such an extent that an overflow took place and the valley northward towards the sea was completely filled with asphalt, which is still flowing slowly downward, though there has not been any escape of asphalt from the lake for some years. That this overflow took place under sub-aerial conditions is proved by the weathered state of the superficial deposits beneath the land-pitch, and by the form of the valley floor. This shows also that the site of the lake had by this time reached a considerable height above sea level, and sub-aerial denudation must have meanwhile been affecting the surrounding country, leaving a remnant of the plateau, but trenching it so deeply on the eastward and south-eastward as to expose the oilrock, but not under such conditions as regards gas-pressure, etc, as to give rise to mud-volcanoes. The flow and exudation may at one time have been fairly rapid, but it is now, naturally, very sluggish, owing

to gradual inspissation. In its latest stage, soil has actually been washed down from the surrounding country over the margins of the asphalt in several places."

The lake is exceeded in size by similar asphalt deposits in Venezuela, where, however, the bituminous material is purer, softer, and more difficult to work commercially. The depths of these Venezuelan lakes have never been ascertained.

Though the evidence of the extrusion of asphaltic petroleum as afforded by pitch-lakes is very striking on account of the concentration of the material in one locality, it is no more significant than the asphaltic deposits that mark the outcrops of oil-bearing strata in many parts of Trinidad. The deposits are usually in the form of flattened and rounded cones strung out in lines along the outcrop, and where no actual exposure of the strata is seen it is often possible to map the outcrop simply by these exudations. They vary in size from a diameter of a few inches up to as much as seven or eight yards, and in height from an inch up to six or eight feet. Where the exudation is rapid and copious the cones often coalesce, and an area of an acre or more may be completely covered with the material. Similarly a flow of asphalt down a gully may be seen occasionally, though it is seldom that such streams exceed one hundred yards in length and eight or ten feet in depth.

The consistency of the material also varies from soft sticky oil to hard compact asphalt that can be broken by the hammer, the softer varieties being the most recently extruded. The skeletons and remains of birds and small animals are not unfrequently found in such soft asphalt deposits, showing where they became mired, and being unable to extricate themselves, perished. The writer on one occasion found a live "morocoi" or land-turtle firmly embedded in a soft exudation.

There is nearly always some evolution of gas with the soft asphalt, but as a rule it is discharged very slowly. In some of the cones there is a deep crater in which a bubble of semi-liquid asphalt rises under pressure of gas from below periodically, perhaps once in two minutes. The bubble ascends to the lip of the crater where it breaks by the formation of a small orifice, allowing the gas to escape with a gentle sibilant sound, while the enclosing film sinks down again. In some parts of the forests where the extrusion of asphalt has been

so copious that a thick outcrop of richly petroliferous sandstone has been almost completely sealed, a weird effect is produced when the asphalt cones are heard sighing around one; the imaginative geologist may weave romances upon this slender basis, and picture the imprisoned oil sighing for the advent of an Exploiting Company by whose powers it will find release.

These asphalt deposits are always more or less mingled with inorganic and vegetable matter, and all the debris lying on the surface of the ground, but in spite of this analysis usually shows a percentage of bitumen of 70 or 80.

In the forests of Trinidad the outcrop of an asphaltic oilsand is usually marked by a belt of stunted vegetation, creepers, and vines taking the place of the larger trees to a greater or less extent.

As an outcrop becomes clogged by the exudation, the sticky oil or liquid asphalt breaks out again and again in the direction of dip, so that we find the escarpment side frequently marked by hard asphalt, while the fresh exudations are towards the dip-slope. Such evidence has more than once proved of value in giving an indication of the direction of dip in a locality where no exposures of solid rock were to be observed.

It has often been suggested that such asphalt deposits are not a favourable sign, that exudation on a large scale must have depleted the oil-bearing strata beneath the surface, and that the oil will necessarily be greatly inspissated and too heavy and viscous. There is a modicum of truth in such suggestions, but in actual practice the geologist need not fear such hypothetical depletion; where he finds an outcrop steadily exuding sticky oil and asphalt, he may be assured that rich sources of oil lie beneath the surface, and that inspissation, though it has doubtless had a considerable effect upon the grade of the petroleum, will not have made it by any means valueless. In California, Mexico, Trinidad, and many other countries this has been proved again and again. In fact we may consider that such asphalt deposits are among the most favourable indications that an oilfield can furnish.

In Trinidad it is possible to walk for miles in the forests without ever being out of sight of asphalt, and near Fyzabad

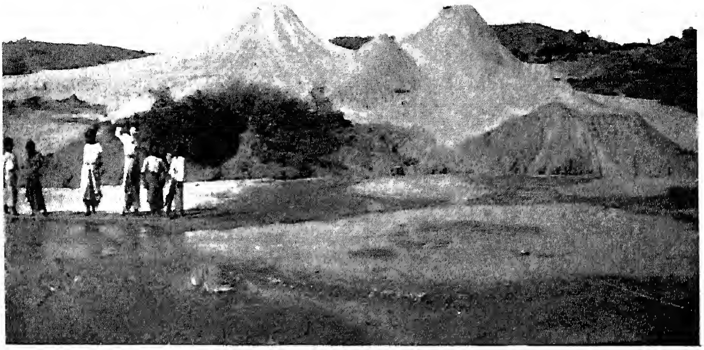

Photo. by S. L. James.

i. GROUP OF MUD-VOLCANOES AT MINBU, UPPER BURMA.

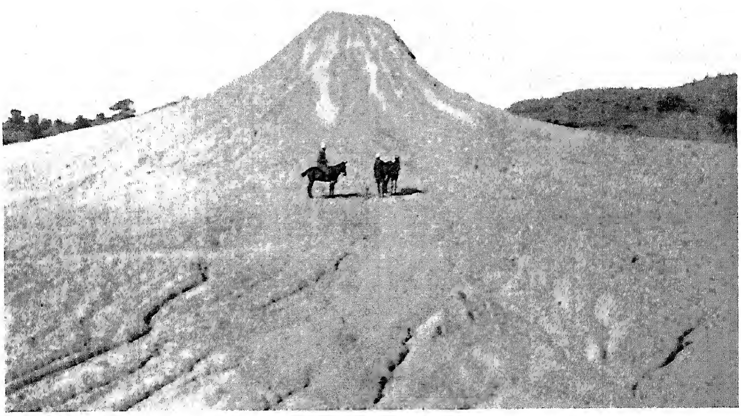

Photo. by S. L. James.

ii. THE LARGEST MUD-VOLCANO AT MINBU.

and Oropuche, and on Morne L'Enfer are localities where more asphalt than soil is to be seen. Such deposits are sometimes worked commercially, but the difficulty with regard to them is that the material is subject to many local variations, owing to greater or less admixture with inorganic matter, and to higher or lower degrees of inspissation. Consequently the asphalt requires some refining to standardize it before a commercial sample of constant composition can be assured. For this reason an asphalt like the lake-pitch of Trinidad with its practically invariable composition is much more valuable as a commercial product, though its percentage of bitumen may be much less than that of some other asphalt deposits.

(*c*) *Evolution of Gas.*—Almost every seepage of oil or exudation of asphalt is accompanied by a distinct evolution of gas in greater or less volume, but similar discharges of gas may take place with little or no sign of liquid petroleum, and it is to these that the term "gas-shows" is given.

The most striking are mud-volcanoes (Plate IX), which must not be confused with the solfataric mud-volcanoes due to true volcanic action. The mud-volcanoes with which we are dealing occur where oil-bearing rocks come near the surface but are covered by argillaceous strata. The crest of an anticline is the most usual position as regards structure, but favourable conditions for the formation of mud-volcanoes can be brought about in various ways. Thus, where an oilrock crops out amidst a great thickness of clays, and the clay has been washed down over the outcrop thus sealing it to some extent, a mud-volcano may be formed. Again, argillaceous alluvium lying upon an outcropping oilsand may furnish a sufficiently impervious cover. Mud-volcanoes may also be formed along lines of fault which permit gas from underlying oilrocks to reach the surface, but this is a rarer phenomenon than is generally supposed. Argillaceous outcrops of an older series unconformably overlaid by petroliferous strata, may have absorbed sufficient gas and petroleum to form small mud-volcanoes. Lastly the sealing up of the outcrop of an oilsand by copious extrusion of asphalt may be so complete that the gas and oil try to force their way through the outcrop of cover-clay and form small mud-volcanoes. Instances of the two latter cases may be seen in Trinidad near Piparo and La Lune respectively.

It is, however, on the crest of an anticline, where the surface is formed of a stiff and thick clay, that the ideal conditions for the formation of a large mud-volcano are afforded. Here the gas-pressure is concentrated continually till during dry weather the surface of the clay cracks, and the cracks gradually extend downwards sufficiently far to allow a little gas to escape. Once a channel of exit is formed it will probably never be permitted to be closed entirely again. The gas issuing under pressure puddles the clay with the help of any surface water available, and through the mud thus formed the gas reaches the surface steadily or spasmodically, carrying a certain quantity of the mud and saline or oily water with it, and thus in the course of time forming a cone. From the evidence afforded by wells drilled near large mud-volcanoes it appears probable that where these phenomena attain to any considerable size, there is either a certain quantity of water in the oilrock or there is a water-bearing band in close proximity above the oilrock. In the case of small cones the water and mud are probably confined to the zone nearest the surface; most clays contain sufficient moisture to allow of mud being formed when the strata are disturbed by discharge of gas, and surface water must enter by the cracks in the surface. The water is usually slightly saline, but not a strong brine.

Professor Carmody has analysed the water from the crater of a small mud-volcano near La Lune, Trinidad, with the following result:—

Total solids	2·506 per cent.
Loss at 180 degrees C. (water of hydration and ammoniacal salts) . . .	0·0149
Sodium chloride	2·04
Alkalinity as Na_2Co_3	0·38
,, ,, K_2CO_3	0·40

and traces of iron, alumina, lime, and potash.

The water also contained a small quantity of petroleum. This volcano occurs beside the outcrop of the Galeota oilsand, where cones of asphalt cover nearly all the surface; the discharge takes place through the outcrop of the cover-clay above the oil-bearing rock. The cone is a small one with a crater four feet in diameter and full of water. Two or three other small cones are to be observed in the neighbourhood.

It is after a long drought that mud-volcanoes are generally most active; this is no doubt due to the parching and cracking of the clay that occupies the surface, an action that extends downwards for a considerable distance.

Mud-volcanoes are of all sizes. Of the number which the writer has observed (nearly one hundred), the smallest has a crater 5 inches in diameter, and the largest a crater of 150 yards diameter. There is usually a surrounding belt of dried mud; this has flowed or been washed down from the crater, which is often raised considerably above the level of the surrounding ground. Sharp cones are more characteristic of the smaller volcanoes, and are formed when there is not a super-abundance of water present, while the larger volcanoes are often almost flat with larger craters often containing much water and soft mud. The smaller volcanoes are usually the most steadily active; the larger are liable to sudden and violent eruptions at intervals perhaps of several years.

All the phenomena characteristic of true volcanic cones are simulated; the flows of mud are exactly like lava-streams; and when a cone has reached a certain height it frequently becomes inactive and another orifice opens on the side of the cone or near it. Thus lines of cones, extinct and active, are seen, reproducing on a small scale the well-known manifestations of true vulcanicity along a fissure.

Strewn about the larger volcanoes, blocks and fragments of rock, possibly brought up from a considerable depth, are frequently seen. A little oil may usually be detected in the water or liquid mud of the craters, and a faint odour of petroleum pervades the whole locality, and is especially noticeable when any fragment of porous rock lying about the crater is broken for examination.

The best known and perhaps the largest mud-volcano in Trinidad is in Columbia Estate in the Ward of Cedros. The usual appearance of the crater is a flat circular area of dried mud strewn with many fragments of ironstone nodules, sand-stone, pyrites, etc. A great number of small cones from a few inches up to two feet in height are distributed over the expanse of mud, and these occasionally show signs of activity. The writer once had the good fortune to see this crater in eruption, but only a part of the crater, which is 150 yards in diameter, was explosively active. A circular orifice of eight

yards in diameter filled with liquid mud had opened towards the north-western side of the crater, and was surrounded by a belt of half-dried mud some 30 yards in diameter, and raised above the surrounding level. At intervals of about a minute the liquid mud rose in a huge bubble and burst, hurling about a ton of mud six or eight feet into the air, while small fragments torn off the mass were thrown some twenty to thirty feet upwards. Every minute cone in the barren mud area was streaming gas and burnt steadily when set fire to. The next day all signs of activity were at an end.

Sometimes the outbursts of a mud-volcano are very violent, especially when its periods of activity are separated by long intervals of quiescence. The "Devil's Woodyard" near Princestown in the Ward of Savana Grande is a good instance. It received its name on account of the uprooting and killing of trees during an eruption that took place in the first half of last century. When the writer visited the locality first, the crater was almost entirely overgrown with vines and bush, and a few small mud-pools, in which a few bubbles of gas could be detected, were the only signs of activity. In May 1906, there was a very violent eruption, which was said by eye-witnesses to have thrown mud over the tree tops of the surrounding forest. After the outburst the volcano presented a very different appearance; the crater is now one hundred yards in diameter and has been raised five or six feet, all traces of vegetation have been buried or blown away, and blocks of a thin band of fossiliferous limestone are to be found here and there on the surface of the dried mud. A few very minute cones distributed near the centre of the crater are still active.

Another volcano close to the southern coast of Trinidad is remarkable for the fact that a flow of mud nearly 250 yards in length stretches from it to the beach (Plate X); from this the name "Chemin de Diable," or its equivalent in the local patois, has been given to this oilshow. Every 10 or 12 years there is an outburst, which is evidently very violent (cp. Plate X), as blocks of rocks up to one foot in diameter have been blown out from under-lying strata, and trees of more than a foot in diameter have been broken off and the upper part hurled away from the centre of disturbance. For the last few years this vent has been practically quiescent, and

Photo. by S. L. James.

i. Bubble bursting in the crater of the largest mud-volcano at Minbu, Upper Burma.

Photo. by. C. S. Rogers.

ii. Part of the crater of a large mud-volcano ("Chemin de Diable") in Trinidad, showing two minor cones.

only a few very minute cones show any signs of activity, and the forest is beginning to encroach upon the area of barren mud.

Lagon Bouff in the Trinity Hills Forest Reserve is another well-known and very active vent. It lies in low ground near the foot of the hills, and consists of a lake of liquid mud 100 yards in length by 60 in breadth. It is in constant activity from two or three centres, and there are occasional violent discharges that can be heard some miles away in the forest.

Besides these well-known mud-volcanoes there are many others of almost equal importance in various parts of the island. Of the smaller cones those of L'Islet Point and those at Galfa Point are perhaps the best formed and most typical.

In Burma in the Districts of Minbu, Thayetmyo, Prome, and Henzada, there are mud-volcanoes, most occurring on the crests of anticlines, though some small ones are apparently formed on lines of fault. Those at Minbu (Plate X) are the largest and best known; they are well-formed cones and are characterized by steady activity rather than by paroxysmal outbursts, owing probably to the oil-bearing strata lying nearer to the surface than in the cases of the large mud-volcanoes described above.

Though it is seldom that much actual oil is discharged from mud-volcanoes, and it may not even be observed at all except where large pools of liquid mud and water fill the craters, there is no doubt as to the presence of oil beneath the surface. The only instances that the author has seen of oil-wells drilled near such gas-vents have all been successful in striking oil.

Evolution of gas often occurs without the formation of a mud-volcano, especially where the strata are hard or sandy, but it may also take place from a clay outcrop. One interesting example of this may be seen in the Ward of Oropuche, Trinidad, where gas issues steadily from the clay soil over an area of about a square yard. This show is situated about the crest of the Central (Western) Anticline. The land has been cleared for cultivation recently, and something in the nature of a regular vent is forming. In the course of time it will probably become a small mud-volcano.

Gas-wells, small pools of water disturbed by steady evolution of gas, are not unfrequent occurrences in oilfields,

and the volume of gas is sometimes sufficient to be used continuously as a source of light and heat. The "Boiling Spring" in Barbados (Scotland District), is well-known; it is kept in a constant ebullition by the gas from an oilsand bubbling through the water. Near Guayaguayare, in Trinidad, there are similar bubbling springs, the gas from which burns steadily when ignited.

All these gas-shows, whether in the form of a great mud-volcano or little gas-pools, are very important evidence, as without sufficient gas-pressure an oilfield may be very expensive to work and the wells may not have a long life.

Another form of gas-show which is sometimes a very helpful sign is the evolution of sulphuretted hydrogen. This may not be connected with petroleum at all, but in many oilfields this gas, only too readily detected by its odour and its action upon metallic silver, is formed by the action of water upon sulphur compounds in the petroleum and its inspissated residues. Where the oil-bearing rock is a limestone, as in some of the "sour" oilfields of Ohio and Indiana, discharge of hydrogen sulphide is not uncommon from the oil-bearing series. The evolution of this gas may be so copious as to be dangerous to life. At Marmatain in Persia, where a sulphurous oil in the limestone bands forms this gas under weathering processes, two Persians lost their lives by going to bathe in a pool in a small gully where the gas had collected on a still day to such an extent that it overcame them; the bodies were not discovered till next day. In the prolific field of Maidan-i-Naphtun also, one of the wells gave a gas with a large proportion of sulphuretted hydrogen, and birds and jackals were found after a still night dead near the derrick.

(*d*) *Outcrops of Bituminous Strata.*—Even when no seepage of oil, exudation of asphalt, or evolution of gas is to be observed, it is generally possible to recognize an oilrock by its outcrop. With an oil of asphaltic base this is a simpler matter than when paraffin oils are dealt with. In the former case there is usually at least a slight bituminous impregnation or discoloration, and the odour of petroleum may be detected even when there is very little coloration. Oilsands are often so highly impregnated that even when the oil is dried up by inspissation at the surface the bituminous content is so high that the rock can hardly be broken by the hammer, but can be

dented or cut, and small projections can be twisted off in the fingers and rolled into pellets in the hand. There are large areas in Trinidad covered by outcrops of this kind, and the material has been quarried for use on roads; the rock crushed under traffic forms a smooth surface that does not wash away easily during rains, nor become hard and slippery in cold and wet weather as does an asphalt surface. The "tar-sands" of Barbados are precisely similar, though not always so highly impregnated.

But when an outcrop has been subjected to weathering for long periods without fresh access of oil or bitumen, it may show very little trace of a former impregnation. In such cases the mode of weathering or the traces of sulphur compounds may be sufficient to prove that we are dealing with an oilrock. Any sand may be an oilrock, but if in examining a section one finds certain bands softer and less coherent, darker in colour, and with rounded contours as compared with otherwise similar sandstones in the same section, it may be presumed that if any of the strata have been, or are beneath the surface, oil-bearing, it is these, and if followed up in the field and studied under different conditions as regards structure and exposure, clear and unmistakable evidence may be forthcoming.

Faint yellow stains or flecks due to traces of sulphur from decomposed sulphur compounds often afford additional evidence, and may be the last remaining traces of a former impregnation.

The coloration due to metallic oxides or sulphides, iron or manganese compounds, may in some cases simulate a coloration due to bitumen, but when the rock is crushed and washed or vanned, or treated with a solvent such as benzine, there can be no mistake as to the nature of the colouring material.

With oils of a paraffin base there may be no such evidence, and when a weathered outcrop is suspected of having been impregnated, it is necessary to break open any nodules or hard and compact bed that the strata may contain to search for traces of petroleum. The more compact and fine-grained the material, the less easily will any impregnation be removed by weathering, so a survival of an impregnation may be discovered in a hard nodular band, when the surrounding more porous and once more highly-impregnated strata have lost all trace of the

former presence of oil. A faint odour of vaseline is often the only evidence that can be obtained. In Trinidad the oils of paraffin base occurring in thin sands among thick masses of stiff clay frequently betray their presence by the residues of an impregnation and the unmistakable odour of vaseline in nodules of iron and lime carbonates found in the clay. In Burma also, where paraffin oils are the rule, the oilrocks at outcrop frequently show no trace of petroleum, and compact or nodular bands have to be examined.

Where the oilrock is a limestone there may be no signs of petroleum at outcrop, but, as pointed out already, crystals of sulphur or evolution of sulphuretted hydrogen may be sufficient to point to the former presence of an oil containing sulphur compounds. The staining of pebbles in a stream by the deposition of sulphides, and the presence of finely divided sulphur in the water, giving it a milky appearance, are pieces of evidence that very frequently characterize outcrops of limestones or shale that contain or have contained an oil with a percentage of sulphur.

(*e*) *Manjak and Ozokerite Veins.*—No account of indications of petroleum would be complete without some mention of the veins of solid petroleum residues, known by various names in different countries, and according to differences in their composition. The solid bitumens, though all closely allied in composition, differ greatly in physical characters such as lustre and jointing, while in such practical matters as melting point, purity and efficiency as insulating material in electrical work, there are also many differences. In the United States Gilsonite and Uintaite are the prevalent names, while a hard and much altered form is known as Grahamite. In Canada Albertite is the designation of a very hard variety. But every gradation between the hardest and most mineralized form and a viscous pure bitumen can be discovered. The author prefers to use the old name Manjak or Munjac as a generic term for all these bituminous minerals; the term has been in use in Barbados since early in the seventeenth century.

Ozokerite is to an oil of paraffin base what manjak is to an oil of asphaltic base, but though there are many varieties of ozokerite the mineral is less common than the solid bituminous minerals, and the term is applied to all grades of mineral wax. The origin of these minerals is the same;

they are the solid residues from the inspissation of petroleum *beneath the surface,* and may be looked upon as intrusive petroleum.

Though it may not be possible in all cases to prove that manjak veins are essentially phenomena of an oilfield or the margin of an oilfield, their association with petroleum has been established so frequently, and they afford in many instances such valuable indications as to where the search for oil is likely to be successful, that we must regard the study of the manjak group of minerals as part of the necessary knowledge with which the geologist who has to specialize in oilfield work must make himself familiar.

The important points to be noted are the conditions under which veins of manjak are found. Briefly put, manjak veins occur where a thick series of strata, partly or wholly of impervious material, overlies a source of asphaltic oil, and where, either due to the softness of the superincumbent rock, to contraction owing to partial drying, or to earth-movement, planes of weakness have been developed enabling intrusion of petroleum from below to take place. Manjak veins are invariably highly inclined or even vertical, except where small local off-shoots from a larger vein may take gentler inclinations. Bedding-planes, fault-planes, joints or minor slip-planes in an argillaceous mass afford opportunities for this intrusive action. The occurrence along bedding planes has more than once led to the belief that manjak is of the nature of coal, and a mode of formation by the sinking of heavy tropical timber to form a deposit in water of not more than one hundred fathoms in depth has actually been suggested and published. Quite apart from its inherent improbability, such a theory fails at once when the facts are studied in the field. The occurrence of manjak among foraminiferal clays, *e.g.* in the San Fernando Manjak field, is hardly compatible with a drift-origin theory, while the fact that the veins cross the bedding in all directions, and only occasionally run along it for short distances, proves that the mineral is not a deposit and must have reached its present position in some other manner. In the United States Mr. Eldridge has described vertical veins of gilsonite which have been traced for great distances through horizontal or nearly horizontal strata, which are trenched by great canons; the orientation of these veins varies very little, and may be due

either to earth-movement or to the drying of the strata caused by proximity to the canons.

In Trinidad and Barbados the mineral occurs in thick masses of argillaceous strata and slip-planes, joint-planes, and occasionally bedding-planes determine the directions of the veins, but irregular pockets are developed here and there. The veins vary in thickness, orientation, and dip, but, as stated before, are nearly always highly inclined. Perhaps the largest vein of manjak that has ever been described is the Vistabella Vein in the San Fernando Manjak field. It attains a thickness of thirty-three feet for part of its course.

Manjak varies considerably in purity and composition, according to the environment in which it is found. It is usual in testing a manjak to treat it with petroleum ether, which removes in solution a percentage which is called "petrolene," while the insoluble percentage is called "asphaltene." The most valuable types are jet black, bright and lustrous, with a beautiful conchoidal fracture and a high percentage of petrolene. Small percentages of water, volatile matter, and inorganic impurities, are always present. The quality of a sample is determined by its freedom from impurities and its percentage of petrolene, since a high proportion of the latter enables the solid bitumen to be fluxed more readily.

Columnar jointing is a frequent phenomenon in veins of manjak, and it may extend across the whole vein, the columns being at right angles to the sides. The columnar variety is usually poorer in petrolene than the variety with conchoidal fracture; it has also a duller lustre and a coaly fracture: The structure is due to the loss of volatile constituents. Every phenomenon of an intrusive dyke or vein of igneous rock is simulated by these intrusive bitumens, and veins may be seen with margins of columnar structure and a central portion of the lustrous conchoidal variety, which represents a later intrusion. The percentage of petrolene also increases towards the centre of every vein, and further increases in analogous parts of the same vein as it is traced to deeper levels, while a vein that does not crop out at the surface generally contains a greater proportion of petrolene than one that is exposed. These facts prove that there is a gradual loss of volatile constituents, and a gradual drying-up or inspissation of the mineral towards the sides of the vein and towards the

surface. Thus a specimen from the 50-foot level in Marbella Mine can be compared with a specimen from the same vein at a depth of 125 feet, the analyses being by Professor Carmody:—

	From 50 feet level	From 125 feet level
Water	0·65	1·0
Organic matter	94·80	96·20
Mineral	4·55	2·80
Percentage of petrolene	8·80	9·6

Specimens from deeper levels in the Vistabella Mine gave percentages of petrolene up to 15·2.

In Barbados, where many of the veins do not crop out at the surface, even higher percentages of petrolene are recorded. One vein gave 18 per cent. from its columnar selvage and 35 per cent. from the central portion.

The clays surrounding manjak veins are often seen to contain sticky inspissated oil or liquid asphalt along joint faces and slip-planes, and nodules of clay-ironstone slightly more porous than the clay show abundant evidence of impregnation. From the centre of a vein with columnar jointing in Marbella Mine the writer has seen a semi-solid bitumen slowly extruding. This material was brittle enough to be broken up by a sharp tap, but could be bent and twisted without breaking if pressure was applied slowly. Its percentage of petrolene was 56; it is a later intrusion.

From this evidence it is obvious that the mineral has been introduced in a liquid or semi-liquid state, and has gradually dried and hardened in situ. A still more convincing piece of evidence is the fact that sometimes when a vein is followed to a considerable depth it is found to end in a sand or sandstone fully impregnated with sticky oil, "tar-sand" as it is called in Barbados. This makes the origin of the mineral quite clear, and its relations to petroleum on a larger scale can usually be established by field evidence. Thus in the San Fernando Manjak field an oilsand, with several "shows" of heavy oil on its outcrop dips steeply beneath the clay beds in which the manjak is worked (Fig. 8), and presumably underlies these strata throughout the syncline. The shaded part in the diagrammatic section shows the zone in which manjak veins have been proved by mining. It is natural to expect that the crest of an anticline

would be the most likely place to find veins of manjak, and small veins have certainly been discovered on or near anticlinal crests where a considerable thickness of impervious argillaceous strata lies above the oilrocks, *e.g.* in the Poole District and near the "Devil's Woodyard," in Trinidad, but the centre of a sigmoidal flexure, between syncline and anticline seems to have

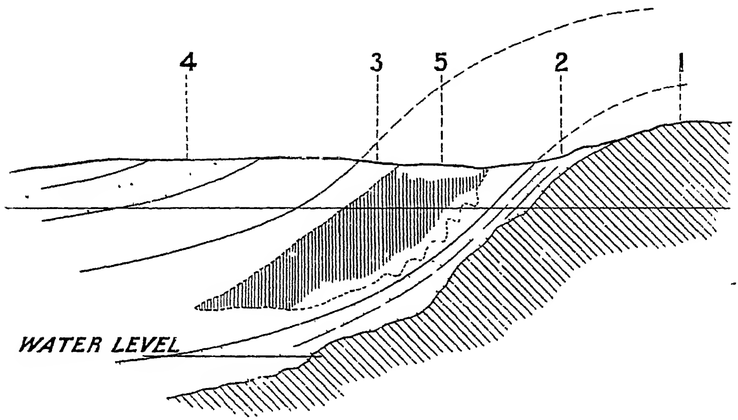

FIG. 8.—Diagram illustrating mode of occurrence of Manjak veins in Trinidad (San Fernando Field). 1. Cretaceous inlier; 2. Oil-bearing sand; 3. Clay; 4. Sandstone; 5. Zone containing Manjak veins.

some special advantages that make it eminently favourable to the intrusion of these bituminous minerals. Probably the strains developed during the earth-movement that caused the flexures have resulted in slip-planes in the argillaceous strata and so favoured the intrusive action. The pressure of gas occluded in or associated with the oil was probably the moving force.

On a minute scale intrusion from the upper surface of an oilrock may frequently be seen. Where the La Brea Oil-bearing Group is exposed in coast-section near the Pitch Lake, small veins of asphalt may be observed extending vertically upwards from the upper surface of the petroliferous sand, and hand specimens may even be obtained of such veins not more than an inch in thickness with portions of the country rock on each side. This is sufficient to suggest the possibility of similar intrusions on a much larger scale, given the requisite conditions.

Ozokerite veins occur under much the same conditions, but

seldom attain to the same size and thickness that manjak veins reach.

Paraffin oils being as a rule more mobile and lighter, and containing less material capable of forming solid residues than asphaltic oils, are liable to find their way further without solidifying as they gradually become inspissated, and are not likely to coagulate in such large masses. Consequently thin veins and networks of veins, and bands of porous inorganic material impregnated with the solid paraffin wax are more frequent than thick well-defined intrusions. The colour of the ozokerite varies from yellowish white to brown and black, but the latter colours are by far the most common. The mineral, being of considerable value, is frequently mined, but the mines do not often become great commercial successes owing to the lack of thick and solid veins.

The occurrence of rock-salt or brine-springs is not dealt with as evidence of petroleum, although the association of brine or salt with oil is frequent in many parts of the world. In a former chapter it was shown that this may not be an essential association, but another indirect effect of the same cause; consequently though the search for brine has often led to the finding of oil, and its occurrence may often give valuable evidence to the geologist, it is hardly justifiable to class rock-salt or brine with surface indications of petroleum.

All the phenomena described above must be noted by the geologist, and the significance of each learnt, so that he may be able to ascertain whether or no a series is or has been petroliferous; evidence may be very scanty in jungle-covered ground, and he may have to rely upon very meagre indications, which might easily be overlooked. It is, therefore, necessary that every variety of indication should be familiar to him. In argillaceous strata he must be especially on the alert; where exposures are few and dips unreliable, a minute gas-show, or the discovery of a few fragments of manjak, may be of great value in assisting him to determine where a test well should be located.

2. Indications in a Borehole.—Evidence that may be considered as "favourable," and as pointing to the prospect of striking oil in a drilled well, may be of almost any nature, and such evidence can only be interpreted by reference to what is known of the geological formation or series that is being tested.

During the first tests of a new presumed oilfield, where perhaps little or nothing is known of the geology of the district, a state of things which even nowadays may be met with only too often, "shows" of gas and oil are really the only favourable indications that can be recorded. And even these may be entirely deceptive, for it may be that such shows are derived from horizons which in other districts are represented by thick and prolific oilrocks, but which have thinned out to insignificant streaks in the area being tested. And the driller may be tempted to drill deeper and deeper into strata that are not and never have been petroliferous. The well may even pass through an unconformability into some lower series, which, if exposed at the surface, would never be tested for petroleum even by that most hopeful of optimists, the driller of wild-cat wells. Yet, because light shows of oil and gas were encountered at some stage or stages, the well may be continued for months at ruinous expense.

On the other hand, when the geology of a district has been carefully worked out, when the strata to be drilled through are known, and the depth to be drilled estimated approximately, a "favourable indication" consists of any evidence that shows that the strata to be tested are being approached, and the fact that *no* shows of oil or gas are encountered may be a favourable indication, proving that the petroliferous contents of the strata beneath are securely sealed beneath an impervious cap and that migration upwards has been prevented.

The recognition of any known band of rock in the log of the well, or by fragments from the bailer, even if it be a prolific water-sand, which will enable the depth to the oil-bearing horizon to be re-estimated, is often of great importance, as where lateral variation in rock groups is the rule estimates of thickness made from some section at a distance can never be very accurate.

When one or two wells have been drilled, information from the boring journals should be sufficient to enable the geologist to judge whether the prospects of a third well are promising or not, and the depth can be calculated with a fair degree of accuracy if the area has been geologically mapped. But without a large scale geological map the boring journals are of very little use unless the wells are close together. In the author's experience estimates of the depths to be drilled have come

within 10 feet of the actual depth in the case of new wells two miles distant from any previous well, and for depths of nearly 2000 feet, in an area of great and sharp flexures. Such estimates were arrived at by careful six-inch mapping and making allowance for the thinning of rock groups owing to an ascertained lateral variation.

Oil is seldom struck without any warning; light gas "shows" or light shows of filtered oil and gas often occur at some distance above the actual oilrock. These are due to a gradual migration from below. Gas is not necessarily a hopeful indication, but when gas-pressure increases steadily as the drill penetrates deeper and deeper into a fairly impervious group of strata, it may be taken as a very favourable sign; the first porous band of any thickness met with will probably be oil-bearing. Even in such a case, however, the oilpool may be missed and the oilsand found to be full of water. An example of this occurred in Trinidad. A light show of oil was struck at shallow depth and cased off; the well was continued and struck strong gas in a sandy shale. The gas-pressure continued to increase as the boring proceeded, and caused much difficulty in the drilling. At greater depths, however, the gas-pressure began to decrease, and when the well reached a thick sand-bed it was found to contain salt water. The gas had reached the locality by lateral migration.

It is, of course, when the first tests of a new field are being drilled that indications become most important, and especially when unknown strata are being penetrated. Though a district may be mapped geologically with great care, and the series proved to be petroliferous, the first well may be drilled into strata that are not exposed for a distance of many miles from the locality. A study of the lateral variation may have made it appear highly probable that oil-bearing strata are beneath the surface, the geological structure may be eminently favourable, and the well carefully located, but, as the depth to be drilled is unknown or only roughly estimated, there is necessarily some uncertainty. It is in such circumstances that the evidence from the log must be most carefully studied. Any light show of gas or oil, if in thin beds, will be a favourable sign. But if thick porous beds are pierced with light shows of gas or oil accompanied by water, the indication is most unfavourable. If the drill has passed through a great thickness

of stiff argillaceous strata, when it first reaches a porous bed important evidence will be forthcoming; if oil appears in the bed the indication is most hopeful, but if water, the prospects of the well are gloomy. The nature of the argillaceous strata have also to be considered; if they are typically marine throughout, the prospects will not be quite so good as if estuarine conditions are indicated by the presence of gypsum or selenite at some horizons, and especially towards the base of the argillaceous group.

Alternating bands of clays and sandstones may be regarded as moderately favourable, even if the sands contain water. Nodules of clay-ironstone,calcareous concretions in sandstones, glauconitic sands, and all the characteristics of estuarine and deltaic beds may be regarded as favourable.

Beds of coal or lignite, if pierced at comparatively shallow depths where comparatively thick clays underlie them, are hopeful indications if the geological structure be good; if struck at great depths, the field will probably have to be abandoned.

Beds of gypsum or rock-salt are indifferent evidence; oil-bearing strata are not infrequently found below them, but just as frequently above them, while in many cases they are not associated in the same series with petroleum.

The occurrence of marine limestone is, generally speaking, a bad sign, though many prolific fields have a limestone as their reservoir rock. An entirely marine series, without intercalations with littoral or estuarine beds, is to be avoided.

Fresh arkoses or grits containing fresh felspars, micas or volcanic material, are usually unfavourable as indicating the proximity of crystalline rocks or volcanic strata which were being denuded while the series was being deposited. The approach to an unconformability, however, which may be indicated by the presence of conglomerates formed of pebbles derived from an older series is often worth noting, as the basal arenaceous groups of a series are frequently oil-bearing under favourable conditions. The reason of this is obvious when we consider the landward margins of a delta, and the probability of the formation of swamps between the main mouths of a river and the higher ground that may bound the delta on one or both sides. Pebbles or fragments of pebbles may frequently be brought up in the bailer, and a bed consisting chiefly of

pebbles can be recognized by any competent driller, so there should be no difficulty in ascertaining the presence of conglomerates.

If a thick arenaceous series, whether conglomeratic or not, is being drilled, and salt water is found in it, there is little hope of an oilwell till some underlying impervious rock group is reached and drilled through.

Favourable.			Unfavourable.	
Always.	Usually	Sometimes.	Usually.	Always.
Shows of oil with strong gas in thin porous beds among impervious strata.	Shows of filtered oil with gas.	Shows of oil with very little gas.		Light shows of oil in thick porous beds with water or brine.
	Evidence of estuarine or deltaic conditions.		Evidence of entirely marine conditions.	
		Beds of gypsum or rock-salt.		
			Brine.	
	Shows of gas below or in a thick argillaceous series.			
	Shows of partially inspissated oil near the surface.		Shows of partially inspissated oil deep down.	
				Water-sands below a thick argillaceous series.
		Lignites or coals, fossil resin, sulphur or sulphuretted hydrogen.	Sulphuretted hydrogen accompanied by hot water.	Hot water with neither oil nor gas.
	Gas in slightly porous strata, with pressure increasing downwards.		Gas-shows accompanied by water in porous beds among impervious beds.	
	Ozokerite or manjak veins.			

But when all is said and done, every case must be considered on its merits by reference to what is known of (1) the geology of the district or country; (2) the stratigraphy of the series that is being tested, and (3) the geological structure in the particular locality. An indication may be exceedingly favourable where the structure is not very attractive, while in a field with ideal geological structure it might give by no means a hopeful prediction as to the results likely to be obtained.

It is therefore almost impossible to tabulate what are, or are not, hopeful indications, and the table on p. 119 must be regarded only as a rough guide to the geologist who has to study well records in a new field. It is presumed that the well has been located *where the geological structure is favourable.*

CHAPTER VII

STRATIGRAPHY

In the foregoing chapters an account has been given of the principal subjects which the prospecting geologist must study in the field before he will be thoroughly competent to advise a company in the exploitation of petroleum. The necessity of elucidating lateral variation has been dealt with, the working out of geological structure has been treated at some length, and the various kinds of evidence upon which a series can be determined to be petroliferous have been described. But this is not sufficient; the geologist must leave little or nothing to chance or guess work. It remains to correlate the facts that have been collected and to get at least a general grasp of the stratigraphy of the country or area examined.

This is not a matter of merely academic interest, but is of very practical utility, for though the directions of variation may be known, though the petroliferous nature of the series be assured, and though an exceedingly favourable geological structure be discovered, there may not be any oil-bearing rock of importance beneath the surface within reach of the drill. Thus, in Lower Burma a well might be located on a good anti-clinal or dome structure, among what used to be known as the "Prome Series," which is undoubtedly petroliferous, and on drilling being commenced the well might very shortly penetrate into the Sitshayan shales, a marine group of great thickness which has never yielded petroleum. Or again, in either Lower or Upper Burma an area of excellent structure high up in the Pegu Series might be tested where the depth to the nearest petroliferous bands might be so great as to make it impossible to reach them, or if possible, at an expenditure of time and money that would effectually prevent the field from being remunerative. Instances of failure under such conditions are only too frequent, and similar cases can be mentioned from

Trinidad, Persia, and Baluchistan. In fact the writer, even with his limited experience of oilfield exploitation, has come across cases of failure owing to neglect of stratigraphical study in every field with which he is intimately acquainted.

It is essential, therefore, that the main stratigraphical groups of a series should be determined, and the geologist must be able to recognize within reasonable limits the position in the series of any horizon that he has to study.

In the course of field-work the geologist will necessarily gather a great number of facts of stratigraphical importance, especially during his study of the lateral variations, for it is those variations which complicate the issue, and make the establishment of a stratigraphical sequence a matter of no small difficulty. A correlation or tabulation of the facts is necessary, and as each new area or district is examined something will be found to add to or modify the correlation previously attempted. Finality, if the area be large, is almost impossible to attain, but the broad lines may be laid down to be improved, modified, or confirmed by future observers.

Where sections through the entire series in which oil occurs are to be observed, the geologist will do well to examine them as soon as possible; he then starts with a sound basis for generalizations. Measurements of the thicknesses of groups of different types of sediment should be made wherever possible and noted for each particular district. Such measurements need not be made on the ground if evidence be abundant and the area be mapped carefully on a large scale; sufficient accuracy will be assured by measurements on the map. Vertical sections of the strata observed should then be constructed for each district or locality.

Lithological characters must be studied closely, but too much reliance must not be placed on them for purposes of correlation; for if variation be rapid, precisely similar conditions of deposition will be found to have occurred at different epochs in different areas, and may occur again and again in the same area. Thus almost any particular variety of strata may occur at almost any horizon in a thick series, and to found any generalization upon resemblance in lithological characters, unless the rocks can be actually traced along the strike from one area to another, may lead to fatal mistakes.

State of Mineralization.—In a thick series, however, there

are some points that may be noted with great advantage, and of these first of all comes what may be generally expressed as the "state of mineralization." When one is dealing with a series of from 5000 to 10,000 feet of strata—and the prospecting geologist will probably have to study a mass of sediment somewhere between these limits—it is only natural to expect that the older deposits have been more greatly affected than the younger by the conditions of temperature, pressure, and circulation of underground waters to which they have been subjected, and the longer period during which these conditions obtained. Thus harder and more compact strata will be observed among the lower horizons than among the upper, even when the sediments are of practically the same composition. Jointing, again, will be more perfectly developed in the older strata, especially in the argillaceous rocks, which are more susceptible to pressure than arenaceous rocks. Thus a concentric weathering and exfoliation may be prevalent among clay groups in the lower part of a series, and altogether absent from similar clays among the higher horizons. The formation of veins, whether of selenite or calcite in clays, and the slickensiding of these veins owing to minute movements, is another point to be noted. *Ceteris paribus*, these are always more conspicuous among the older horizons. If the series contain lignites or coals, they and their underclays usually furnish easily recognizable evidence, the tendency being for the older carbonaceous deposits to have become harder, blacker, better jointed, and, as proved by analysis, to have lost water to a greater extent than the younger, while the underclays develop at least the rudiments of stratification, which they may not exhibit till subjected to considerable pressures.

Among arenaceous strata the solution of iron compounds or calcium carbonate, and their redeposition in cementing laminæ, or concentration into concretions, are effects which have required time as well as the necessary conditions as regards pressure, temperature, and presence of carbonated water; so younger strata may give very little evidence of such action, the effects of which are common enough in strata of greater age.

All these minor points, none of which is of great importance in itself, may by their cumulative evidence enable the field-student to detect the difference between a lower or middle horizon and an upper horizon in the series, or between upper or

middle and lower horizons, so that in dealing with a considerable thickness of strata, exposed in an inlier and perhaps unconformably overlaid, some idea may be at once suggested as to the position in the series of the horizons exposed. It must be remembered that these points of enquiry are of chief value in Tertiary strata, where the youngest rocks are very little altered since their deposition. Where folding has been intense, and on a large scale, the mineralization of strata has naturally proceeded further than in undisturbed regions, and this must be taken account of when comparing strata from different areas.

Alteration in Character of Sediment.—Frequently, also, it may be found that the detritus from which sediments are formed has altered in character as the series is ascended; pebbles of some particular rock may be found in the upper or lower beds alone; if this is found to hold good over a wide area it becomes of great importance as proving that different strata were being denuded at different times. Thus in the Yaw sandstones at the base of the Pegu Series, pebbles of agate are frequent in some parts of Upper Burma, but throughout the rest of the series they are absent, and it is not till the post-volcanic stages of the succeeding and unconformable Irrawaddy Series that agate pebbles are again observed in the Tertiary sediments. Similar instances could be given without number, but this will be sufficient to illustrate the point that the constituents of an arenaceous group may on occasion furnish a clue to its age.

Details of this kind may be noted on the vertical sections made for different districts, and may be of great help in establishing the stratigraphical relations of different groups.

Fossil Evidence.—Of all aids to correlation and the working out of a stratigraphical sequence that will hold good over large areas, there is nothing more valuable than fossil evidence, provided that it is abundant, and that it is made use of in a practical way, as the handmaid rather than the mistress of stratigraphy. Let no practical geologist take upon himself to despise the evidence that he may glean from fossil fauna. Their collection and study may entail a great deal of extra trouble, and many a weary day spent indoors, but any definite results obtained are certain, and may enable correlations to be made that cannot be accomplished by any other means.

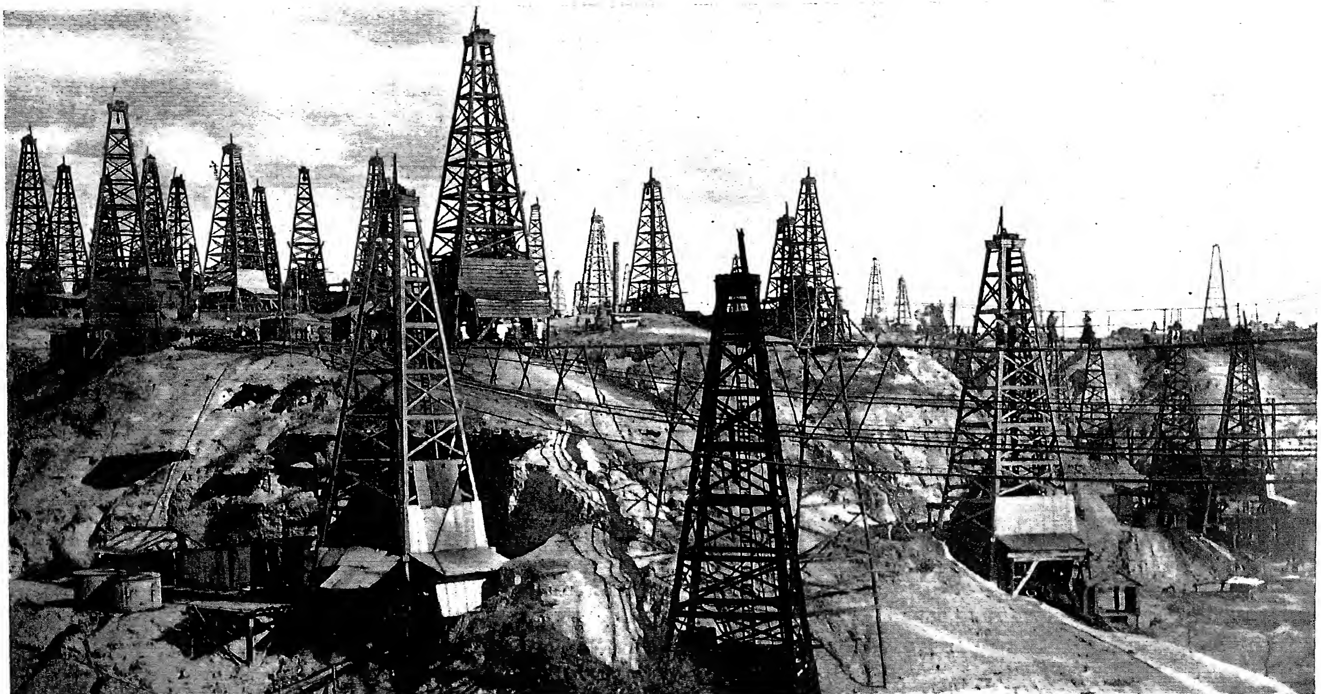

Photo. by M. Croulıansky.

A CORRER OF THE TWINGON OIL-RESERVE, BURMA.

The writer confesses to have little patience with the zoological side of palæontology, and even to be indifferent as to the name that may be given to the fossil part of any particular organism, but he has had experience of what can be done in the way of correlating isolated and far-separated areas by the careful mapping of fossiliferous horizons and the collection of their fossil organisms, even where faunal change in time is slow and the species many and often ill-preserved.

Even if the field-student be not interested in palæontological work, even if he be ignorant of the generic names of the organisms, he will do well to collect and label them carefully, and note on his vertical sections the horizons from which they were obtained. Let him call them "Tom, Dick, and Harry" if he will, so long as he can recognize them again and can point to the horizons from which they were collected.

It may be of interest, and of use also, to the petroleum geologist if a brief description is given here of the methods of handling palæontological evidence, originated and put in practice by the Burmah Oil Company's Geological Staff.

In Burma one of the chief difficulties is in the correlation of different fields, as the petroliferous Pegu Series appears frequently in widely separated inliers. These inliers are overlaid unconformably by the fluviatile Irrawaddy Series, during or previous to the deposition of which there was extensive and sometimes very great denudation of the underlying strata. Thus the local base of the Irrawaddy Series may be found resting upon almost any horizon in the Pegu Series, and measurements downwards from the base of the upper series are useless as an aid to the determination of horizons in the Pegu strata as a whole. The amount of pre-Irrawaddy denudation varies greatly within short distances. Added to this there is a lateral variation in the Pegu Series so great that correlation of areas by a study of lithological characters is practically impossible, unless the areas are close together, while the main groups of strata in any field thicken and thin out with bewildering rapidity, so that the whole series, even where the upper part is not removed by denudation, varies greatly in thickness in different districts.

The area examined by the Geological Staff of the Burmah Oil Company up to date is approximately 20,000 square miles, most of it, however, covered by younger deposits than the

petroliferous series. The Pegu Series at its greatest development reaches a thickness of at least 10,000 feet. It will be readily understood that the problem of working out the stratigraphy, so that the thickness of strata containing petroliferous beds should be known in each district, and the horizons exposed in each inlier identified, presented many difficulties.

Luckily there was a considerable mass of evidence from boring journals available, but it would have been of little value without palæontological evidence, which is abundant, almost every inlier containing at least one and generally two or three rich faunas.

Some means had to be devised to enable correlations of isolated areas to be made, and palæontological evidence, if available in sufficient quantity, was obviously suggested. It was ten days of continuous rain when encamped in a very fossiliferous district that first turned the writer's thoughts towards an enquiry as to whether there was sufficient faunal change through the Pegu Series to allow of its being subdivided into zones.

Dr. Noetling of the Indian Geological Survey had published seven years previously a memoir ("Palæontographica Indica," Vol. I.) on the fauna of the Burmese Tertiary rocks, describing and figuring two hundred and eight species, and attempting a stratigraphical arrangement of the sections examined up to that time. Comparatively little of Burma had been gone over by then, and many of the fossil collections were made by previous observers, the localities from which some of the faunas were obtained were but vaguely known, and the relative positions of different beds in the series were uncertain. Thus in spite of the ability with which Dr. Noetling marshalled the evidence, he was handicapped at the start by mistakes in stratigraphy inevitable when no large-scale mapping is done. The mistakes were also made of referring every section examined in Burma to a type-section in the Prome District, of arbitrarily subdividing the series into a supposed fossiliferous and non-petroliferous upper division and a petroliferous and non-fossiliferous lower division, and of treating the local faunas as "zones." Every geological observer who has done work in Burma since the publication of Dr. Noetling's Memoir, and has started with it as a basis, has helped to bring about almost inextricable confusion, from the effects of which the official work of the Indian Geological Survey in the Burmese Tertiaries is only beginning to emerge.

The Geological Staff of the Burmah Oil Company when driven perforce to study fossil evidence in the attempt to correlate different areas, began by making vertical sections of each field surveyed, marking the horizons of each fossiliferous bed and each oil-bearing band. Mapping was usually done on the six-inch, but occasionally on the eight-inch scale, so it was possible to make fairly accurate estimates of the thicknesses of strata exposed. The faunas collected were then compared with Noetling's faunas treated as if they were "zones," but arranged in a somewhat different order from that published in the "Palæontographica Indica," as it very soon became apparent that some modification in his stratigraphical arrangement would have to be made.

Areas where many fossiliferous beds at different horizons were found soon demonstrated that there is considerable faunal change in time relation in the Pegu Series, and a number of rough graphs or diagrams were made use of to illustrate this, still using Dr. Noetling's "zones" as a basis. The "zones"

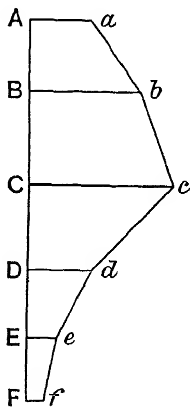

Fig. 9.

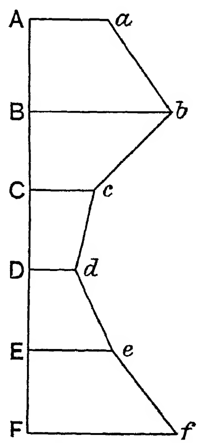

Fig. 10.

A, B, C, etc. were arranged vertically, and distances A*a*, B*b*, etc. were measured off horizontally in proportion to the number of species common to the zone in each bed (Fig. 9).

Joining the ends of these horizontal lines we get a figure *abcdef*, which in the case illustrated indicates that the fauna of the bed under examination resembles the fauna of zone C most closely, but is probably somewhat higher in the series. The

method is rough and open to many objections, but if the zones contain a sufficient number of species, and the fauna to be examined is a rich one, an ambiguous diagram such as Fig. 10, which leaves it doubtful whether the bed should be placed near the top or the base of the series, is hardly possible. Another advantage is that the breadth of the diagram shows at once if the fauna be a rich one or not; the greater the number of species in a bed, the more weight is naturally given to the evidence obtained from it.

Many difficulties had to be encountered. For instance, the discovery of species not described by Noetling tended from the first to complicate matters. This difficulty was partially got over by procuring such books of reference as were available: Dr. Martin's beautiful figures and descriptions in "Die Fossilen von Java" proved of great assistance.

Then it was found that Dr. Noetling's zones did not make a satisfactory basis, some of his faunas are littoral, some laminarian or pelagic, and some indicate brackish water conditions; some are very rich in gasteropods with few lamellibranchs, and others contain numbers of lamellibranchs while gasteropods are poorly represented. It became evident that true zones were required, not faunas from single beds.

Several sections were mapped and measured from the base to the top of the Pegu Series, and all fossiliferous beds in them carefully collected. It was possible then, by a comparison of the vertical sections, to combine them and place many of the faunas in their true relative positions. The measurements of the thicknesses of groups were of great use in this, though owing to the thinning and thickening of different parts of the series no fossil bed could be placed in the series entirely on such evidence, unless it was confirmed by palæontological data.

A range-table was tentatively constructed; it contained between 280 and 300 species arranged horizontally, while the horizons were arranged vertically. A small diagonal cross marked each occurrence of a species, and every occurrence of the same species lay upon a vertical line indicating the range of the form so far as it has been ascertained. The majority of the forms dealt with were gasteropods, which were not only more easily identified than the lamellibranchs, but which seemed to show more marked changes in time relation. The lamellibranchs, however, proved of great value, though the

ranges of some forms are apparently very long. Echinoderms, crustacea, and corals proved very useful, but they do not always occur in sufficient numbers in the littoral beds which are usually the most fossiliferous members of the Pegu Series. Fish, mammals, foraminifera, and one solitary brachiopod have been made use of; in fact, the occurrence of every organism found was recorded on the range-table.

Dr. Noetling's faunas were made use of after being placed among the faunas as nearly as could be ascertained in their true stratigraphical positions.

After the range-table was constructed, it was divided horizontally into seven zones by means of horizontal lines at convenient intervals.

When any new fauna was discovered, and the species identified, it was compared with the faunas of the several zones by means of the graphs or diagrams mentioned above. There was very seldom any doubt as to the zone to which a fauna naturally belonged. Having ascertained the zone, the fauna was then compared with the chief faunas in the zone and its relative position towards them ascertained, and if there was no doubt as to its position the new fauna was at once put upon the range-table. Comparison of vertical sections was of great assistance in the placing of a new fauna.

The first range-table served very well, but it soon became out of date. Faunas from all parts of Burma were constantly being brought in, and great numbers of entirely new species came to light. In fact, evidence accumulated so rapidly that additions and modifications were constantly being made. The attempt to reconcile carefully-measured sections with Dr. Noetling's stratigraphical arrangements proved a matter of difficulty, and after the same sections that he describes had been carefully mapped, new vertical sections were substituted for his, and it was decided that when a new range-table had to be constructed Dr. Noetling's faunas should be omitted, and the stratigraphical arrangement of fossils based upon the four or five complete sections from base to the top of the series which were available.

The new range-table deals with approximately one hundred rich faunas and numberless beds containing only a few species. The number of species and distinct sub-species or variations is between 450 and 500. The work, the magnitude of which only

gradually became apparent, can perhaps never be complete; the collection in the Company's geological office numbers many thousands of specimens, nearly all of which are in a good state of preservation. All doubtful identifications have been rejected and are not entered on the range-table.

The length of range of many of the forms, and these often among the commonest, has proved disappointing, but in this the accumulation of material has been of benefit, as with more and better specimens it is often possible to detect variations and to split a species into two sub-species, one being characteristic of the lower part of the series and one of the upper.

The occurrence of certain types in certain provinces and apparently not in others was one of the initial difficulties, but this has gradually yielded to the effect of more and more evidence being brought forward: the fauna of the Pegu Sea at any epoch seems to have been fairly constant over the area in which it has been studied.

The series is now divided into five main zones, and further subdivision is possible. Though seldom more than sixteen or twenty species are found only in one zone, the ranges of many of the forms are sufficiently short to be of great stratigraphical value. Any mixed fauna of twenty to thirty species can usually be placed without any difficulty in its true stratigraphical position, and a difference of 200 feet in horizon between two rich faunas can be shown by diagrams. The collection of fifty species from one bed is by no means a rare occurrence in Burma.

The methods employed in dealing with such a mass of palæontological evidence are at the best rough and ready, and may not commend themselves to palæontologists generally, but the practical use of fossil evidence for practical purposes connected with oil development has been the point always aimed at. Many species have no doubt been incorrectly named, many even of the genera may not have been determined beyond the possibility of doubt, but the ten thousand feet of the Pegu Series have been divided into zones which have held good up to the present, the effects of lateral variation have been abundantly proved, the advance of the delta has been determined beyond the possibility of doubt; it is possible to state with a fair degree of accuracy what zones in each district will be petroliferous and and what zones barren, and every bed with a rich fauna can be

placed in the series within one or two hundred feet of its true position, and datum lines for the correlation of any new field are furnished. Many details also of the geology of Burma, details of which it would not be in the interests of the Burmah Oil Company to permit the publication at present, have been brought to light.

It is not intended that this palæontological work of the Burmah Oil Company's Geological Staff should be taken as an object lesson by the field-student; this brief account of it has been given merely to show what practical value can be derived from the study of fossils by a staff, none of whom would claim to be specially qualified as a palæontologist. It is urged upon the geologist who is engaged in oilfield work to collect such fossils as he may find, and to label them carefully for future study. They may prove of great assistance at some future day, although apparently of little interest or importance at the time that they were collected. So long as palæontology is kept in its proper relation to field-mapping, so long as generalizations are not founded upon the sporadic occurrence of a few species, but on evidence from a large thickness of strata and a wide range of organisms, every fact that can be brought to light and tabulated will be of service.

The idea of a range-table is to safe-guard against sources of error, for a few wrong identifications from a bed containing many species may not affect the final result appreciably. The more species collected and identified from a bed, the more certainty will be attained in assigning it to its stratigraphical horizon. It is a very old proposition, but never more aptly illustrated than in palæontological work, that a correct conclusion is more easily reached by considering a great number of minor points, none of which may be in itself of supreme importance, but the cumulative effect of which is great, than by seizing upon three or four salient facts and founding a generalization upon them.

CHAPTER VIII

LOCATION OF WELLS

Any practical operator, manager, field-superintendent or driller, who has been good-natured enough to read so far in this little book may well exclaim "Now at last we come to practical politics: what can this geologist tell us about the locating of wells?" With the spirit of such a reader the writer heartily agrees. All that has gone before is leading up to this one important matter, the choosing of the sites for oilwells, so that the oil-bearing strata may be struck with a minimum of trouble and expense, and under conditions that should yield a maximum production.

It is, of course, in the case of the first test-well of a new field, or presumed field, that the importance of carefully selecting a site is most forcibly brought home to us, and it is this aspect also which appeals most to the general public. The geologist who undertakes oilfield work will soon weary of the oft reiterated question, "How do you know where to put a well?"

There are many methods of actually making a first selection. It is told of one well-known and very successful exploiter and driller in the United States that he frankly stated that his method was to put on an old and cherished hat, and to gallop a rough horse about the country side or farm till the hat dropped off. On the spot where it fell he drilled the well. The story is at least *ben trovato*, and it is possibly quite true.

The writer knows one highly productive and very valuable field, miles from the nearest surface indication, where the first test-well site was selected in almost as haphazard a fashion. Drillers and field-superintendents had met to make the location, and the area in which a spot was to be selected was generally determined, but with characteristic caution none would venture

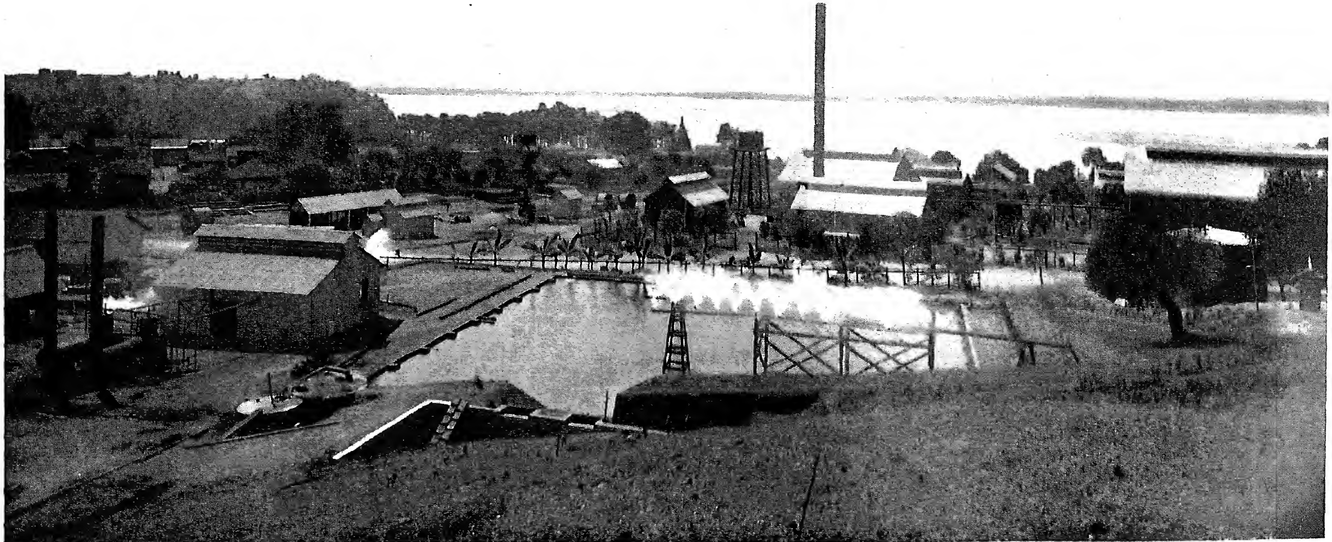

Photo. by M. Croulìansky.

THE PUMP STATION, NYAUNGHLA, UPPER BURMA.

The field-end of the Burma Oil Company's famous pipe line.

an opinion before the others as to what exact spot should be fixed upon. At last, one bolder spirit than the others, spoke up and said, "Well, boys, if it's all the same to you, let's put the well where that crow sits down," pointing at the same time to a crow which was flying about them. The crow alighted, the spot was marked, and the well drilled with remarkably successful results; it is still producing after eleven years. A flight of a hundred yards or so further to the eastward would have put the well beyond any hope of striking oil.

Well-sites, in fact, have been selected for very many reasons; the colour of the soil, or the proximity to an oilshow have frequently been responsible for the erection of a derrick at a particular spot. The divining rod has been utilized occasionally, and sometimes with successful results, while complicated instruments have been invented and put on the market to enable any one to detect the presence of oil beneath the surface, but as to whether or no there is any scientific basis for the working of such instruments the author must plead ignorance.

But the ordinary workaday geologist must not depend on quasi-supernatural aids nor little understood inherited instincts. By his geological map he must stand or fall, for he will soon appreciate the fact that, however good and careful his work may be, it is upon the wells that he locates, especially in new fields, and upon the results obtained from them, that he will be judged. An error of judgment made, a fact lost sight of, a calculation not checked and rechecked, an allowance not made for some condition that may be inferred but cannot be observed, and the well may prove a failure, with the effect that his reputation as a practical man may suffer undeservedly.

The popular idea that petroleum is a very capricious and uncertain mineral, and that the only way to be sure of finding it is to drill a borehole, is rapidly dying out, but still it is not possible to drill for oil with the same confidence with which one can drill for water. It is often impossible to be sure whether there is petroleum beneath the surface or not, but fortunately it often is possible to be quite certain that oil will *not* be obtained by drilling.

When the series has been proved to be petroliferous in the particular district, when the stratigraphy has been worked out,

and it is known that oil-bearing horizons are within reach of the drill, and when the geological structure has been proved to be favourable, the striking of oil becomes almost a matter of certainty. In such a case, when the geological map on a large scale has been completed, the locality for the first test-well is indicated beyond a doubt, and it only remains to select the most convenient spot for access, transport, water supply, etc. within that locality.

But though the map shows the exact spot that should give the most favourable results, it will be the task of the geologist to *find that spot on the ground*, and to see that no mistake is made in marking it. This is the more important as the first geological survey, though entirely correct as regards structure, may not be accurate as regards topography; the well must therefore be located according to the geological structure rather than according to the topography.

In symmetrical domes and anticlines a position upon the highest point of the crest is indicated, that is to say, where the crest reaches a maximum height geologically speaking, and probably quite independent of the surface contour of the ground. Towards such a locality oil and gas will naturally tend to migrate, gas pressure should be highest, and production greatest.

But even in this case it may be advisable to select a site slightly removed from that theoretically indicated, for purely practical reasons. Where gas-pressure is likely to be very great and the structure is favourable to a great concentration towards a crestal point, a well might encounter great difficulty by striking a violent discharge of gas before any oil is reached, and it might be necessary to allow the gas to blow off for months before drilling could be continued into the oilrocks, and oil produced in any quantity. If the gas could be controlled and utilized at once, there could be little objection to the drilling of such a well, but this might not be possible in the circumstances, and much valuable gas-pressure might be dissipated before the well could be brought in. In such cases the well often drills itself in, but this is seldom a satisfactory result, as the handling and anchoring of casing may be prevented by the rush of gas and oil. A well, however, located slightly down the pitch or the flank of the flexure is not so likely to meet with the same difficulty, but will probably be a producing oilwell as soon as the oilrock is reached, so that

a much better idea of the capabilities of the field will be obtained without delay.

It is possible that in very few cases is gas stored at the crest of an anticline to the exclusion of oil, but it is quite probable that gas may be struck before the oilrock is reached, and the pressure may be great enough to cause damage to plant, if not even loss of life, when a well suddenly taps such an accumulation of gas under very high pressure.

In those cases where large mud-volcanoes occur on the crests of anticlines, similar precautions must be taken in locating the first well. High gas-pressure and possibly flows of mud may make the drilling very difficult, if not impossible, on the crest of the flexure, while a well slightly down the flank may not suffer from the same disadvantage. The geologist must judge from the results of wells drilled under similar conditions in the same country, or from his experience in other countries, whether there be any danger of a well proving troublesome in this manner.

When the dome or anticline is asymmetrical the well must be placed not on the crest but on the flank on which the gentler dips occur. This is owing to the hade of axial plane of the flexure, and the reason is obvious when a horizontal section through the fold is drawn to scale. Mr. E. H. Pascoe has explained this point very clearly in the "Records of the Indian Geological Survey," Vol. XXXIV., Part iv., 1906, where he gives a formula by which the distance from the crest at which a well should be located on an asymmetrical anticline can be calculated, as follows:—

$$l = d \tan \theta + \lambda$$

where l is the distance from the crest to the well, d is the depth of the well, θ is the angle of hade of a plane through the apex of the fold, and λ is the distance between what he calls the "apex-locus" and the "crest-locus." Thus a well at A (Fig. 11) will just touch oil in the petroliferous bed 1, while a well at D will strike oil in the oilrocks 3 and 4, but not in the higher beds 1 and 2. The angle θ must be found by observation: it is half the difference between the steepest dips observed on either side of the crest *in the same bed.* Thus, if the maximum dip of a bed on one flank is 90°, and on the other flank 10°, θ will be $\frac{90^\circ - 10^\circ}{2} = 40^\circ$.

This formula is of great practical value in determining the best position for a well, when some evidence is to hand from the other wells in the vicinity. It leaves, however, several details to be worked out practically. Thus, unless the depth d to be drilled is known approximately, it is impossible to find a

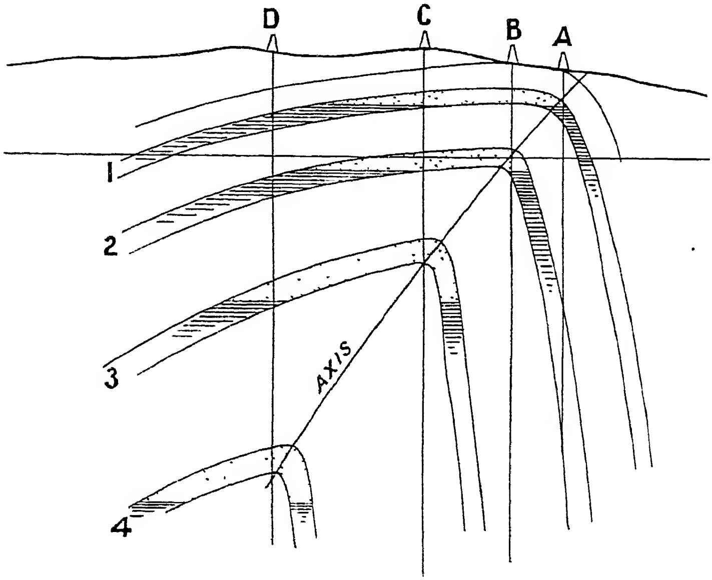

Fig. 11.—Section of Asymmetrical Anticline. Dotted portion shows extent of oil-impregnation.

value for l. Again, the distance λ, which will also vary according to the depth, must be found by calculation; it depends on the shape and sharpness of the flexure, which may vary greatly in different localities. It should be possible to calculate λ from observation, when the strata are well exposed. It will almost certainly decrease gradually as lower and lower horizons are reached.

But the calculation of d is a matter of greater difficulty, unless evidence from other wells is available, or the oil-bearing horizons are known through very careful stratigraphical work. Thus in a new field that is to be tested it will be expedient to place the test-well so that the crest will not be crossed at the greatest depth to which it is proposed to drill. This may necessitate the missing of the oilpools at shallow depths, so

the geologist must consider each case on its merits and locate his well for deep or shallow oilrocks as is most convenient or most likely to prove of value to the company developing the area. As a general rule, it will be found better to exploit the shallow sands first, once the presence of oil has been proved, stating the depth to which each well is to be drilled, while another well can be located further from the crest to test deep oilrocks.

One point with regard to asymmetrical anticlines and domes seems to have been lost sight of very frequently, and that is,

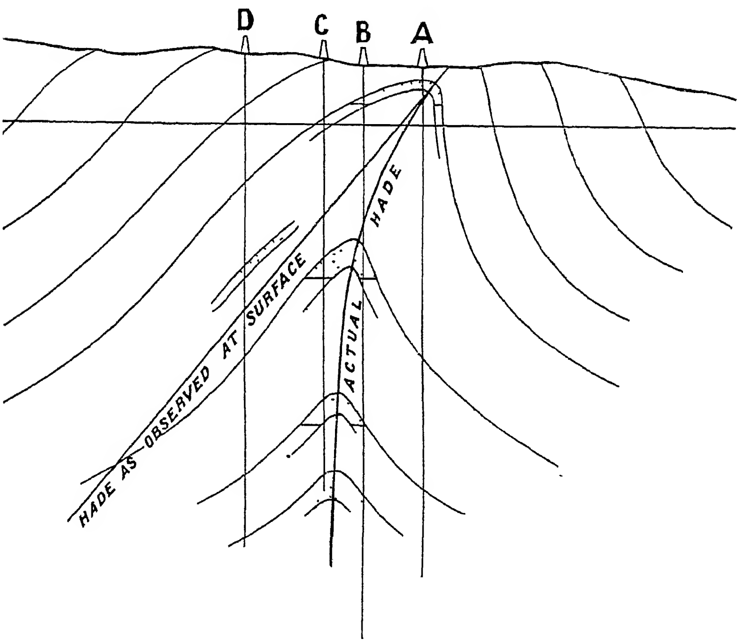

Fig. 12.—Asymmetrical Anticline, showing decrease in Hade of Axis. Dotted portion shows extent of oil-impregnation.

that the hade of the axial plane in any flexure is not constant. Tracing the axis along the flexure, the hade is seen to decrease or increase, but it is not so readily admitted that traced downwards into the heart of the fold the hade must decrease. Yet when we consider that the flexure has been caused by tangential stress, it is obvious that the hade of any asymmetrical flexure must decrease downwards, and finally disappear altogether. In Fig. 12, which represents an asymmetrical fold on

a scale sufficiently small to include practically the whole of the flexure, it will be seen that the hade of the axial plane decreases rapidly, and that to calculate on its remaining constant and to drill on that theory would be to court failure. Again, it will be seen that at a certain distance from the crest the hade beneath the surface has practically died out; no well need therefore be drilled further from the crest than this point, the approximate position of which can usually be arrived at by a careful study of sections taken across the whole flexure. No formula can be given for finding the distance of this point from the crest, but as it will be a suitable place for all wells greater than a certain depth, it should be the geologist's endeavour to ascertain the position of the point as accurately as possible and to locate the deep test of the field upon the line indicated.

Another point is illustrated in the section. It will be seen that in a well which has been placed too far from the crest, a thin bed of porous rock has been pierced almost on a level with a thicker oil-bearing band which forms the crest of the fold. It is not an unfrequent phenomenon to encounter a show of gas and filtered oil in a thin and probably lenticular band placed in such a position. The oil which it contains has come from one of the main oilrocks, and has been filtered during its migration. It is struck at a depth much less than that calculated for the main oilrock that the well has been drilled to strike. The occurrence of this show of filtered oil is very naturally regarded as a hopeful indication, and the well may be continued to a great depth, though owing to the decrease of the hade of the axial plane it is impossible to strike oil in the main oilrock. Instances of this have come under the writer's knowledge more than once, and till the whole underground structure of the field has been clearly proved, it may be impossible to satisfy oneself, or those responsible for the exploitation of the field, that the show of filtered oil need not be a hopeful indication at all.

These considerations apply chiefly to highly asymmetrical anticlines, where the flexuring is sharp. In flexures that are only slightly asymmetrical and are not very sharp, it matters very little on which side of the crest the well is drilled. It is possible to obtain oil in quantity from the steeply-dipping flank of an anticline, but it is obvious that the reservoir on that side can never be so large as on the more gently-dipping flank. The migration of petroleum towards the crest is also a simpler

matter in steeply-dipping beds, and a well-defined water level may quite possibly be found on the steeper flank considerably above the water level on the gentler flank. This is due to the hydrostatic pressure of water, which, according to theory, probably underlies the oil; in steeply-dipping beds the separation of oil and water by migratory movements along or up the bedding planes is naturally favoured more than in gently-inclined beds. Accordingly, it is always as well to make locations on the gently-dipping flanks of anticlines whenever they show asymmetry. Another reason of a practical kind emphasizes this desirability; the mechanical difficulties of drilling through steeply-dipping strata are, in most cases, much greater than when the strata are gently inclined, and the tendency of the bore to depart from the vertical position, and for the sides of the borehole to cave, are always greater, the more steeply the strata are dipping.

The asymmetry of a fold very frequently changes when it is traced some distance, and the actual hade of the axial plane may change from one side to the other; hence in every locality the amount and direction of hade must be ascertained as carefully as possible and locations made according to the circumstances in each case. Where there is any doubt as to the position of the crest at any particular depth, to make sure of reaching the oil horizon on the gently-dipping flank rather than on the steep flank should be the geologist's endeavour. Except in long anticlines with little or no sign of dome structure, and where the oilpool is consequently very narrow, there should be little danger of missing oil if the effects of hade are carefully worked out.

When flexures are intensely folded, or even overfolded, as in some cases in Galicia where a single oil-bearing stratum has been pierced three times at different depths in the same well, the conditions are apt to become so complicated that it is impossible to state any general proposition that will serve as a guide in locating wells so as to give the best yield. But it is as well to remember that a water-level will be found somewhere in almost every oil-bearing rock, however well isolated by surrounding impervious beds. The geologist, in estimating the area from which a production of petroleum is probable, and the area likely to be drained by a well, must go by such evidence as is available either from other wells in the same area or from

productive wells in other areas, assuming that an oil-water-level will be discovered, and leaving the local variations in this hypothetical plane between water and oil to be proved by actual drilling. Local variations due to differences in porosity, splitting, thinning out, or lenticularity of porous beds, and seepage across fault-planes are very common, but cannot be reckoned upon till proved by the evidence from a number of bores.

In locating wells to prove the extent of a field in which oil has already been struck, the geologist must use his common sense when guiding evidence is deficient. Thus if an anticline exhibits dome structure, that is to say, if well-defined pitches point to the length of the field not being excessive in comparison with its breadth, the oil reservoir in each productive stratum will be deep, and it may be possible to locate profitable wells far down the flanks or pitches of the flexure, while if the fold be little affected by pitches a shallow, long, and narrow oil reservoir may be expected. In any case the geologist will find it expedient to feel the way cautiously towards the limits of an oilpool, rather than to locate wells rashly in the hope of proving a wide field at once. It is hardly ever profitable to drill an unsuccessful well, as the evidence it furnishes is almost entirely negative, and does not necessarily assist those in charge of drilling operations in defining the limits within which profitable productions can be obtained. On the other hand when water and oil are found in the same stratum when pierced by a well, when the occurrence of the two liquids can be demonstrated in intimate association, very valuable evidence as to the extent of the oilpool may be furnished. As stated above, it is useful and even necessary to assume that there is a regular level between oil and water in each bed, a horizontal plane above which oil, and below which water, will be struck, but in actual practice, especially where the oil is of high specific gravity, it may be exceedingly difficult to determine where such a plane can be drawn in horizontal sections. In simple and well-defined structures, where the porosity of the oilrocks is fairly constant and the oil of light gravity, there may be little difficulty, but even in such a case the plane may be at different levels on opposite sides of an anticline. It is a useful convention, but it must not be regarded as a hard and fast line which cannot be affected or altered by local conditions. There are many cases on record of water being struck in a well and

pumped for months before oil has made its appearance in any appreciable quantity, and yet the well has finally yielded oil without any admixture of water and continued to give a profitable production for years. Thus the actual striking of water where oil is expected does not always mean that the well is a failure. Again, what is called a "freak well"—a deplorable phrase—may be brought in outside what has previously been accepted as the limits of profitable drilling. Of such freaks there is always an explanation, though it may be by no means obvious; in many cases such so-called freaks could have been foretold, had the geological conditions been studied with sufficient care.

Many of the discrepancies between predictions and results nowadays are attributed to lenticularity of the oil-bearing strata. Oilsands are doubtless lenticular, as deltaic and estuarine deposits must necessarily be, and as for that matter every clastic deposit in the world must be. Among the rapidly deposited sediments of a delta thinnings out and variations are naturally especially conspicuous, but, all things considered, the lenticularity of oilsands is being made too much of. To shelter oneself behind "that comfortable word" lenticularity when predictions as to the depth and position of oil-bearing strata, or the prospects of a well, have gone astray is a confession of weakness, ignorance, or, still more probably the want of careful detailed mapping, which the geologist should be ashamed to make unless he is in a position to prove out and out that such lenticularity exists. As a general rule, if he can prove striking lenticularity in the beds exposed at the surface he may be justified in assuming it among beds of similar character and mode of formation underground. In any case he should be able to ascertain the general directions of lateral variations, and should thus have the key to any problem involving the sudden thinning out of beds of porous strata capable of containing petroleum, or the sudden appearance of such strata. To depend upon well-records for such evidence is at the best to obtain information at second-hand, and it is not in every field that well-records can be implicitly relied upon, the personal equation entering into them to such an extent that, even where carefully kept, they may leave many essential points doubtful. To advocate drilling down the pitch or the flank of a flexure in the hope of striking a lenticular bed impregnated with oil and

sealed from the invasion of the dispossessing fluid, water, by being surrounded by impervious strata, is to reduce geological science to the level of guess-work. Yet wells have been successfully brought in under such conditions and have proved very remunerative, though the locations have been disapproved of by geologists on grounds perfectly justifiable. It is such instances that have often discredited geological work in the minds of practical and unscientific oilmen, and it makes the geologist's task all the more arduous to know that unexpected and even unprecedented conditions may falsify the conclusions at which he has arrived after the most careful consideration of structural and practical evidence from every point of view. It is for this reason that the study of lateral variations has been insisted upon with such emphasis; oilsands can be shown to be splitting up, thinning and dying out by evidence visible at the surface, as the directions of such splitting, thinning, and dying out can be ascertained beyond question; is it unjustifiable to assume that similar variations must exist beneath the surface, and that from what can be actually seen we may interpret the subterranean anomalies of which we only obtain direct evidence through the drilling of wells? Lenticularity of beds may be a very important factor in oilfield work, but to assume it as an explanation of facts that have not been anticipated may be merely a begging of the question. In locating wells upon an anticline, especially if it be of considerable extent and length, all these matters must be considered, and it is rash to assume that an oil horizon proved at one end of an anticline must necessarily persist to the other end, even where the structure is eminently favourable for a production of petroleum.

In locating wells upon a monocline or a terrace-structure, the geologist has, as a rule, a very simple task. He will be guided first of all by any local variations of dip or strike that may be observed, and secondly by the presence of surface indications. Where the dip decreases locally, or where there is a sudden change of strike, especially if the bend in the strike is concave towards the direction of dip, the locality will generally have better prospects of production than areas lying to either side. In a terrace-structure, where the oil-bearing strata do not crop out at surface, this has been proved in many instances; in monoclines attention is usually called to

such favourable localities by the "shows" at outcrop, for it is at such changes of dip or strike that the petroleum tends to be concentrated and frequently appears at the surface.

It only remains to calculate at what depth it will be advisable to strike the oil-bearing rocks, to measure off a sufficient distance in the direction of dip, and mark the location. On terrace-structures it may not be possible to calculate the depth; and the procedure will be as in the case of gentle anticlines with a slight degree of asymmetry.

When locating on a monocline it may be taken for granted that a water-level will be found somewhere, though it is possible that both oil and water may be encountered together throughout a considerable thickness of strata. This depends largely upon the specific gravity of the oil, and, as by gradual inspissation at and near the surface the oil in an outcropping petroliferous band must, however slowly, lose its lighter constituents and become heavier, a final stage may be reached when the oil approximates in specific gravity so nearly to that of water that replacement by the latter cannot be complete; consequently a definite water-level, even if proved in one locality, may not be constant over any considerable distance in the outcropping oilrock. But it is as well to assume that a water-level will be reached sooner or later, and, therefore, the oilrock must not be struck at too great a depth. At too shallow a depth gas-pressure may not be great enough to ensure a good production, and the oil may be too much affected by inspissation. It follows that the making of a location requires the exercise of judgment and will be governed chiefly by experience of results obtained in similar strata and structures and with similar oils. Localities where the dip is lowest will be selected in preference to those where the inclination of the strata is considerable for several reasons; in the first place because it is then possible to place the well further from outcrop for a given depth, and secondly because seepages at outcrop may not have depleted the petroliferous bands to such an extent. A depth of 400 feet is very suitable for a first well when the strata are inclined at an angle of 20 degrees or less. This gives a minimum distance from outcrop of between 1100 and 1200 feet. If the strata dip very gently, the depth need not be so great in a first test. After one successful well has been drilled, the next can be placed to strike the oilrock

at greater depth, and the limits of the area which will prove profitable to drill felt for cautiously.

With beds dipping at 45 degrees or more, 600 feet will not be too great a depth for the first test-well. In the case of light paraffin oils, as has been explained before, such tests may be quite unsuccessful, but with oils of asphaltic base excellent results may be obtained under such conditions.

The calculation of depth is a matter of great importance, especially as the shutting off of any water-sands that may be found above the oilrocks is absolutely essential if good results are to be obtained. Given a careful geological survey of the area there should be no difficulty in calculating the position of the oilrocks and the water-sands beneath the surface at any point, and it may be possible even to draw contour lines showing the approximate depths. But the field-student must be warned against projecting the angles of dip as observed at the surface and so attempting to delineate the underground structure. Such methods as those used by the mining engineer in calculating at what depth a shaft must be sunk in any locality to strike a lode will, if applied to oilfield work, often give results so inaccurate as to be useless for practical purposes. It must be remembered that any monocline or any inclined bed represents part of the great curve of an earthwave, and that the part seen at the surface is infinitesimal compared with the part concealed beneath, so that the angle of dip, however carefully measured, may not be very useful as a guide. The drawing of horizontal sections to scale, when there is sufficient evidence, will make this obvious at once, and will emphasize the futility of projecting a dip as seen at surface, as if it continued indefinitely without increase or decrease. It is expedient, therefore, to make a careful horizontal section before attempting to make locations, provided, of course, that the section is *made to scale from a geological map*, and is not merely the diagrammatic absurdity produced by an observer who has made no serious attempt to map the ground geologically. Thus we come back to the proposition stated above that the location of wells should depend entirely on the geological mapping, and provided that this has been done with reasonable care there can be little doubt as to where a test-well should be placed.

It would serve no useful purpose to take every kind of

geological structure, and give in detail an account of the conditions which should determine the site for a well: in spite of elaborate classifications of structure, all structures known in an oilfield can be considered under two or three comprehensive heads. But a few words are necessary about areas where faults are a conspicuous feature. Great care must be exercised in locating wells in faulted areas, not only because the fault plane if pierced during the drilling may be the cause of great mechanical difficulties, making the keeping of the bore vertical and the sides from caving by no means an easy task, but because the presence of faults in the near neighbourhood may

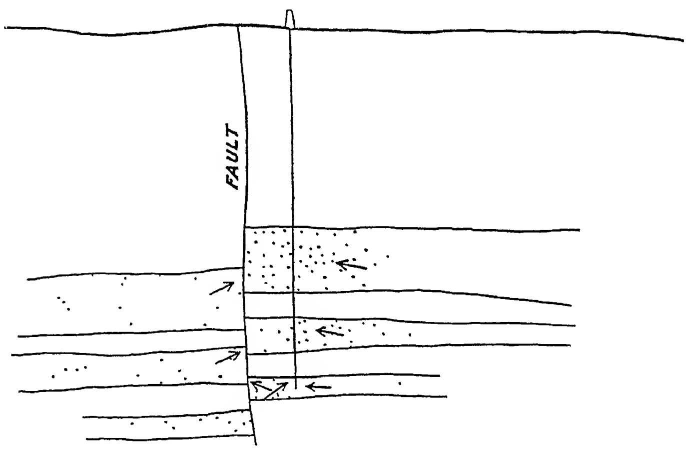

Fig. 13.—Diagram showing how a small fault may enable a well to tap a great thickness of oilrock locally. Arrows show movement of oil and gas.

have great effects upon the production of the well. The theory that faults affect a field adversely by allowing migration of oil along the fault-plane has already been dealt with and disposed of, but by allowing communication between separate oilsands *across* the fault-plane a dislocation of the strata may have remarkable results (Fig. 13). The field-work of several observers has proved that many of the greatest fountains in the Baku field lie close to the line of a fault, which has made possible communication between separate oilsands, which are both thick and numerous, so that a well on or near the line of fault is able to derive oil from many horizons, and to tap

them, so to speak, all at once. A somewhat similar case can be cited from the Yenangyoung field in Burma, where Mr. B. F. N. Macrorie, of the Burmah Oil Company's Geological Staff, has shown how small faults of little structural importance have assisted in raising the production of certain wells far above the average, and limiting the productiveness and life of others.

As a general rule it may be taken that it is always preferable to drill on the upthrow side of a fault rather than on the downthrow side. The reasons for this are easily understood when it is remembered that any fault can be theoretically replaced by a sharp fold; on the downthrow side the throw of the fault may be sufficient to bring the horizon of an oil-bearing band below water-level, while with normal faults, hading to the downthrow side, the well may encounter the fault plane and get into considerable mechanical difficulties. In many cases what is seen as a fault at the surface becomes a sharp fold when traced downwards where the elasticity of the beds is greater, especially when thick and soft masses of argillaceous rock are present. Faulting when it occurs in a series where by far the greater part of the strata is impervious, and the porous oilrocks widely separated, may be of great importance, as an oil-bearing band that would otherwise be found cropping out at the surface may be cut off and isolated among the impervious strata. The oil contents may be preserved thus from inspissation and great productions may be obtained from a band isolated in this manner. It will be observed that the throw of the fault may not be a matter of importance in this case; either an upthrow or a downthrow may effect the isolation. It is obvious that careful geological work is necessary before it is possible to locate wells to take advantage of structures such as that shown in Fig. 13, but in many fields unexpectedly large productions have been struck by the drill entering a band of oilrock which has been preserved from weathering and the loss of light oils by being cut off in a similar manner.

Faults, generally speaking, unless they are dislocations of great size and throw, are more helpful than harmful in an oilfield, for the simple reason that in most productive fields the total thickness of impervious strata is in excess of the total thickness of porous rocks. Their presence may complicate

the geological map and make the calculation of the depth to be drilled in a well more difficult, but their presence need not have any deleterious effect upon production.

Questions of accessibility, proximity to water supply, expenses of road-making, etc., must all be taken into account when making a location for a test-well in a new field, but all these matters, though serious items in expenditure accounts, must be regarded as secondary to finding the site most favourable according to the geological conditions. The young geologist may have pressure brought to bear upon him to fix upon some alternative location which seems "almost as good" as the one he had originally selected, or which may perhaps be in a locality where the prospects of obtaining oil are doubtful, but which is much more easily accessible and will not necessitate any great expenditure in road-making, transportation of plant, and furnishing with a water supply. He will do well to resist all such suggestions, because it is a short-sighted policy that advocates a first test-well in any but the most promising locality available. The cost of drilling a deep test-well in a new field is usually so greatly in excess of the expenses incurred in road-making, providing water supply, etc., that these may be disregarded. If the more accessible site be chosen, and after months, or, if any difficulties be encountered in the drilling, perhaps more than a year spent in completing a deep test without successful results, another well costing probably nearly as much and taking as long to drill will have to be tried before the area can be considered fairly tested. On the other hand if the best site, geologically speaking, be selected at first, and the test be unsuccessful, the area may be abandoned at once, and all the time and expense of drilling a second well saved. It may often be difficult to convince field-managers or managing directors that an area can be thoroughly tested by the drilling of one well, but if the geological work has been done thoroughly one test should be sufficient in almost every case, and when the first test is unsuccessful the throwing away of time and money by making further tests is a matter the blame of which must be largely at the door of the geologist, unless his advice has been arbitrarily overruled.

Very frequently a geological adviser finds himself in the position of having to advocate the testing of an area to a certain depth, and after that depth has been reached without striking

oil it may be necessary to say at once, and as definitely and strongly as possible, that there is no further hope, and that the area should be abandoned. In such a case, if the well be "in good shape" to be carried much deeper, there may be considerable hesitation on the part of those responsible for the practical operations in deciding to abandon it. The geologist, having the courage of his own convictions, should make things as easy for the field-manager as he can, by putting the case clearly and concisely before him. Little blame can be attached to the unsuccessful testing of a new field by drilling one well, as it is often impossible to make sure of the petroliferous character of part of a series in any particular locality without evidence from a borehole; but to allow a second unsuccessful test to be drilled, or the first to be continued to a great depth when it has no further prospect of striking oil, is a confession on the part of the geologist of the uncertainty of his own judgment or his ability in reading the evidence obtained during the geological mapping of the ground. Hence it becomes of the utmost importance that no testing of a new field should be commenced till the geological examination has been made in detail and the location made in the best possible place to obtain a production of oil. Were the importance of this principle more fully realized, the popular idea of the capricious nature of petroleum would be shaken, and might even be relegated to the limbo of scientific fallacies.

After a successful well in a new field has been drilled, the second test should be placed so as to develop as large an area as possible without taking the risk of getting beyond the margin of the oil-reservoir. This is to enable some idea of the area available for drilling to be obtained at once. When there is great doubt as to the extent of a field, the best policy to adopt in developing it must necessarily be uncertain, but with a fairly accurate idea of the minimum size of a new field, drilling programmes and transportation of plant can be taken in hand in the most economical and adequate manner. The only exception to this is when the petroleum is required, and can be handled, at once; new wells may then be started near the first test. This, however, is a state of things by no means usual in new fields.

Second and third tests should not be located directly down the dip from the first producing well, but at some distance to

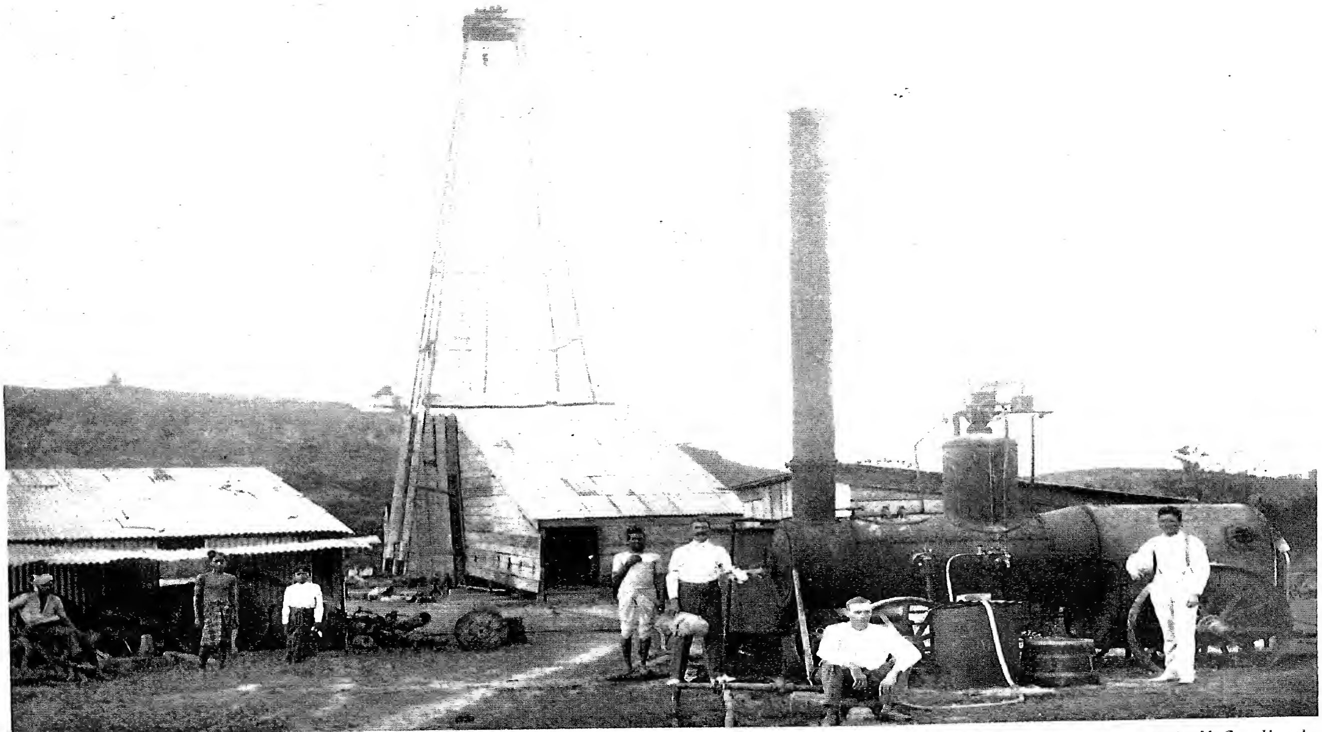

Photo. by M. Croulîansky.

A CANADIAN STEEL-DERRICK AT MINBU, UPPER BURMA.

the side, so as not to interfere with the supply of oil to the first well. The natural migration of petroleum will be up the dip-slopes in most fields, whether in monoclinal or anticlinal structures. If the first test-well has been placed on one flank of a symmetrical anticline, the second may be located on the other flank, in order to obtain information as to the breadth of the field. In a dome structure the second test should be made in the direction of the larger axis of the dome.

The distance at which wells may be placed from one another without mutually affecting their production is a question upon which it is impossible to dogmatize, as it depends upon so many factors, such as the porosity of the oilrocks, the grade of the oil, and the gas-pressure, which may be different for any different field. It may be taken as an axiom that in any given field there is a certain minimum number of wells which will exploit the area most profitably and economically. To drill more than that minimum number will not ensure the production of more oil in the long run, but less, for though production may be more rapid, gas-pressure will be dissipated more quickly, and thus the motive force that brings the petroleum into the well, and perhaps up to the surface, will be to some extent wasted. Fields such as Spindle Top, in Texas, and Twingon, in Burma, might have had very much longer lives and produced much more oil with a fraction of the expense, had there been any regulations to prevent over-drilling.

With light paraffin oils, high gas-pressure and porous sands, a distance of one hundred yards between wells will probably be found a convenient and sufficient distance. When the sands become partly exhausted or clogged near the bottoms of the wells by the deposit of solid paraffin, new wells may often be drilled with profit between the old producers. In shallow fields with asphaltic oils, and in oil-bearing limestones, wells may be placed considerably closer without seriously affecting each other, but in each field the requisite minimum distance must be ascertained by experience.

In calculating the number of producing wells which a proved area will carry it is advisable to allow for a distance of from 200 to 300 feet between each.

Though it is no part of the geologist's task to give advice as to the methods to be made use of in drilling, practical experience in oilfields will soon make him *au fait* with the chief

mechanical difficulties that the driller will have to overcome, and it will be part of his duties to acquaint the field-manager or driller with the nature of the strata through which the well will penetrate.

This will enable those responsible for the drilling to select the best methods for overcoming the difficulties which each kind of rock will present, and the type of rig and tools most suitable will be chosen. Thus through a thick soft argillaceous group it may be found most profitable to use a rotary rig, while drop-drills and under-reamers may suit a variable series containing hard calcareous bands.

The approximate depths of probable water-sands, the presence of hard bands upon which it will be possible to ground casing, the occurrence of soft beds liable to cave into the bore-hole, are all points upon which the geologist may give information that will be of great value to the practical driller. Again, the angle of dip, if it is high, is an important matter, since steeply inclined beds are frequently liable to cave, and if thin hard beds are encountered dipping at a high angle there may be great difficulty in keeping the bore vertical.

Thus, in return for the information afforded to him by the log of a well the geologist should be able to forewarn the driller of difficulties, and so ensure that they are taken in hand and overcome most expeditiously.

CHAPTER IX

(For Beginners)

FIELD WORK

In the preceding chapters allusions to geological mapping have necessarily been very frequent, and it is hardly necessary at this stage to insist that the object of all geological field-work must be in the end to make as complete a geological map as possible. No casual examination of an area is sufficient, no spending of a few hours, or even a few days, if the area be large, in examination of sections and oilshows and the taking of notes will qualify the geologist or petroleum expert adequately to advise those who are undertaking development work. It used to be one of the distinguishing points between the amateur and the professional geologist that the former was frequently content with the drawing of a horizontal section, while the latter alway pinned his faith to a map, but nowadays the amateur is learning that in any case the map must be made before the section, and that nothing but a map will suffice. In oilfield work the whole concession or area, and frequently a large area outside of it, must be mapped geologically.

In some cases a published geological map may be available, and may be of great assistance, but it is not likely to be on a sufficiently large scale to give the details which are essential, if wells are to be located with accuracy to strike the oil-bearing deposits at the determined depth. The best topographical map available must be procured, and if it be on too small a scale it may at least serve to check distances and compass-bearings in the large scale map which the geologist will prepare for himself. The smallest scale that is at the same time sufficiently large to admit of mapping in detail will be naturally selected; for most fields and field-geologists the scale of six inches to the mile will be found to meet the case. Eight inches to the mile is also a very useful scale, and in producing fields scales of sixteen or

twenty-four inches to the mile may be used with profit, and may, indeed, be necessary; but for all practical purposes, especially in new fields and in wild and unopened country, the six-inch scale is probably the best.

Experienced geologists will pardon the writer for giving some account of the methods of field-mapping that he has found most effective under different conditions, in the hope that some of them may prove of value to the prospector or field-student, for whom this little book has been written.

Many of the details to which much attention is given in large-scale mapping in Britain can be neglected, partly or wholly, in oilfield work, and on the other hand methods and conventions that are not required in ordinary geological mapping may become of the greatest importance when an oil-field is being surveyed. It is necessary that structure be worked out thoroughly, and it is for this reason that the mapping must be done on a scale sufficiently large and in sufficiently great detail to make any mistake in structure impossible. But the nature of the strata and the mapping of outcrops with great accuracy, and determining the exact positions of points may in many cases become matters of minor importance. The determination of the exact position of the crests of sharp anticlines, the angles of hade of the axes of asymmetrical flexures, and the pitches of axes is essential, and consequently observations may have to be taken very frequently and with great care, while the angles of dip on the flanks of a flexure may not be considered of sufficient importance to demand any special care in the taking of observations.

Equipment.—The geologist who undertakes the examination of oilfields must have an effective, but not necessarily an elaborate equipment. The first essential is a good and substantial map-case. The large leather map-case as used by the Geological Survey of Great Britain is a very good model, though it may be improved in details to suit the individual. It allows six square miles of ground on the six-inch scale to be studied at one time, without changing maps, an ample area for all practical purposes. It is slung from the shoulder by a strap and can easily be manipulated with one hand; this may seem a very trivial point, but it is really of great practical importance. Smaller map-cases or mounted and folded maps carried in the hand or in a bag or pocket will be found troublesome to manipulate, and do

not conduce to good geological mapping. The tendency will naturally be not to consult the map frequently enough, and the mapping may become more of the nature of taking occasional notes. The possession of a good handy map-case opened and managed with one hand will do much to teach the field-student practical mapping and the reading of geological maps.

Plane-tables, though excellent for careful work in small areas, are too cumbersome: the geologist has very seldom sufficient time at his disposal to make use of such appliances, and the slight gain in accuracy obtained by using them is more than counterbalanced by the laborious nature of the work and the waste of time involved.

Cavalry sketching-boards, fitted with a compass and designed for use on horseback, are pretty little toys. They may be of use on a preliminary traverse or a pioneer exploration of new countries, but they are too small for detailed and accurate work, while the compass is usually also too small to take bearings with sufficient accuracy. Furthermore, if the possession of such an equipment has the effect of inducing the young geologist to imagine that efficient geological work can be done on horseback, it may be his ruin so far as practical field-work is concerned.

For instruments, the first essential is a good pocket compass, one at least two inches in diameter, with a clearly marked dial, that will enable the observer to take bearings to within two degrees. This compass should be carried in a case from which it can be taken and manipulated with one hand. The saving of time, trouble, and, it may even be added, temper, that is effected by carrying a compass that does not require two hands is enormous; this can be understood when bearings have to be taken once at least in every fifty yards, as is necessary when working in dense forest. It is as well to have this compass combined with a clinometer sufficiently reliable to take angles of dip without an error of more than one or two degrees.

For taking bearings from distant points a good large prismatic compass is necessary; it must be sufficiently sensitive to read correctly to half a degree, but the needle must not be too "lively." That is to say, though sensitive, the card should have a comparatively high "moment of inertia." This will enable readings to be taken by the method of oscillations, and another great saving of time will be effected. The geologist

will soon learn to recognize the happy mean between too great mobility and too great sluggishness in a prismatic compass.

An Abney's level, or some similar instrument, is sometimes necessary in taking readings of the angles of pitch and dip where these have to be measured very carefully, but it need not be carried always. In producing fields and open ground it is far more likely to be required than in new and unexplored country.

Theodolites, tachyometers or omnimeters are often of great value in open ground, especially where there is no topographical map available, but it is impossible for the geologist to carry such instruments with him in rough jungle work. The young geologist should have no ambition to make himself a third-rate land-surveyor, and though it is necessary to understand the use of these instruments, and to be able, if it is required, to measure a base-line with them, he will be well advised to use them as little as possible; to give undue attention to the more or less mechanical duties of land-surveying may run away with time that may be more usefully employed in geological work. Like the Abney's level the omnimeter or tachyometer may be left at headquarters, and only taken out when some special work with it becomes necessary.

A good protractor adapted to the scale used in mapping must be procured. This may have to be made specially of ivory or aluminium according to the taste of the geologist. Ivory is perhaps the better material, though it warps badly in hot weather. The six-inch protractor used by the Geological Survey of Great Britain, and furnished on the back with handy tables to enable thicknesses of strata, depths and gradients to be calculated rapidly, is quite the best instrument of the kind for six-inch mapping.

A hammer may be carried if required, but in Tertiary strata it will not often be used; a cutlass, machete, dah or kukri will be as effective, and will serve other useful purposes, *e.g.* in clearing a path through thick jungle or in digging down a grass-grown section to lay bare the strata.

A stout walking-stick with a crooked handle by means of which it can be hung on the arm when using the map-case or compass is almost invariably carried by the writer. In taking the dip of a ripple-marked sandstone it may be laid upon the the surface of the rock and the clinometer placed upon it. In

slippery or soft ground or in rock-climbing it may also be very useful, and in tropical countries where snakes are numerous it may be necessary as a weapon. The carrying of a stick is, however, a matter upon which the individual must decide according to his inclination.

Pencils, hard or soft, will be chosen to suit the material upon which mapping is done, and the climate, whether wet or dry. A few coloured pencils will be found of great use, and they should be carried so that the colour of each can be seen, and any one selected and brought into use with one hand. A good india-rubber is of course essential.

As to the material on which the mapping is to be done, the author, after trying many varieties from tracing linen to Whatman's boards, has come to the conclusion that oiled paper mounted on linen combines the greatest number of advantages with the fewest defects; it does not shrink or stretch appreciably, it is not rendered useless by damp, takes pencil and chalk marks clearly, and keeps a good surface even after much rough usage. It is advisable to have the paper cut accurately to fit the map-case. Thus for the ordinary six-inch map-case the mapping-paper should be cut in rectangles of twelve by nine inches.

Some observers favour squared paper for field work, but if it is really to be of use it must be adapted to the scale on which the mapping is done. It must tend also to make field work too mechanical, and does not teach the field-student to train and depend upon his eye.

A note book is often useful, but is not absolutely necessary; all notes of importance *must be put upon the field-map.* Descriptive notes, lists of compass-bearings, or fossils collected from various horizons, and small details of mapping or sections shown on a larger scale than that employed on the map can be kept in note books, but as a rule all these can be put in condensed form on the field map.

Finally a strong water-proof bag or satchel, capable of holding the map-case during rainstorms, and with an extra pocket for other instruments, is an essential part of the geologist's equipment. Willesden canvas is a very suitable material for such a bag, especially when bound with leather and slung on a strong leather strap for an attendant to carry.

The geologist will do well to carry all the instruments he is constantly using himself. Hammer, Abney's level, and occasionally cutlass and prismatic compass may be carried by one of his attendants, but everything else should be disposed about his person in such a manner that it can be brought into use with the least delay and fumbling. It may be thought that these are trivial details, the neglect of which can be of no possible consequence; but if the field-student has to work in the tropics in a temperature of 100 degrees Fahr. or more in the shade and 160° or 170° Fahr. in the sun, he will find that even trifling details become of importance, and trifling annoyances may be magnified into trials. To have to wait while a lazy native servant comes up with the instrument required, and slowly unloads a bag in search of it, to have to hunt for a coloured pencil among several concealed in a pocket, when the required one is always the last to appear, and to repeat these performances fifty or a hundred times a day is enough to become a serious worry to the geologist struggling with climatic conditions to which he is not accustomed, and his work may really deteriorate and become less careful through lack of attention to such details. Again, the time occupied in the making of a geological survey is often a matter of great importance. Rival geologists may be in the field, other interests may be represented by other prospectors, and it may depend largely upon the speed with which the main points of a structure are elucidated that the success or failure of the company or syndicate for whom the geologist is acting will turn. Everything, therefore, that favours rapidity in field work, without decreasing efficiency, is to be cultivated.

Armed with the equipment set forth above, the geologist may go anywhere and map any ground in the world, provided, and on this the success or failure of his work depends, that he adapts his methods of survey to the particular variety of ground with which he is dealing. The dense forests of Central or South America cannot be attacked in the same manner as the barren hills and plains of India or Persia.

It is presumed that the aspirant to become a petroleum-geologist has had some training in geological mapping on a large scale before he is called upon to attempt the survey of a new territory, and if he has had experience of mapping in Britain on the splendid six-inch maps of the Ordnance Survey,

he will start with a great advantage over others who have not been so fortunate. The areas which he will have to survey in new countries where the oilfields of the future are waiting for development, have in all probability never been mapped topographically, and he will have to start with blank paper and construct his own map. In such cases everything will depend upon the methods by which the survey is conducted.

Survey in Open Ground.—If the ground be open and largely bare of vegetation, the matter is fairly simple. A base-line, or still better, two base-lines meeting at an angle, must be measured and marked clearly on low and, if possible, level ground, where their extremities can be viewed from the surrounding country. Triangulation by prismatic compass from and to the extremities of these base-lines will give a sufficient number of points to form a skeleton upon which to construct a geological map. Of course such a method is not, and cannot be, entirely accurate, as the readings of compass bearings with a hand prismatic compass cannot be vouched for within less than 30′, but a map can easily be constructed by means of numerous readings and check readings that will be quite accurate enough to ensure that no error in geological structure is possible. Should the area prove eventually to be a productive field, careful land-surveying will have to be undertaken sooner or later, and topographical maps accurate in all details constructed, but that is not a matter for the geologist.

The length of the original base-lines will depend upon the size of the area to be mapped, and the nature of the ground; a quarter of a mile will usually be sufficient. The distance must be measured carefully by chaining, or, if such instruments be available, by means of a tachyometer or omnimeter. An alluvial plain, if the area contains such, is naturally the best place for such measurements. The angle between two base-lines must be read very carefully by means of an omnimeter or by prismatic compass. The positions of prominent features, hill-tops, isolated rocks, or trees, conspicuous bends in the courses of streams, etc., in the immediate neighbourhood are determined by taking bearings from the extremities of the base-lines, and thus a series of points is obtained from which secondary points of importance can be fixed upon and marked on the map. As many check readings as possible

should be taken in determining new points, and where discrepancies occur, and the triangle of error is large, the readings which are most nearly at right angles to each other must be taken as the most reliable. The top of the paper upon which the mapping is done should always be taken as true north, and the magnetic variation allowed for in plotting the results of the observations made: if the variation be to the eastward, it is added to the readings of the prismatic compass, and if to the westward, subtracted. Many square miles can be mapped by this method, beginning with base-lines of not more than a quarter of a mile in length, and the resulting map should be sufficiently accurate to make the working out of geological structure, and the location of wells to test the area matters of practical certainty.

Topographical details, except in the case of important cliff or river sections which must be mapped carefully, can be sketched in as the geological work proceeds, and must be regarded as of secondary importance to the purely geological mapping.

Once the skeleton of the map is prepared, the mapping in fairly open ground will not be a matter of difficulty, as there will always be some point visible from which bearings can be taken. The principal section across the general strike of the strata, preferably a cliff, river, or road-section, will be mapped in detail in order that the natural subdivisions into which the strata range themselves may be ascertained, and prominent groups of beds differentiated and selected for following out through the area. Upon the selection of such groups a great deal depends, especially where variations are frequent and rapid; unless such main divisions of the geological series can be determined, the construction of an efficient geological map is impossible. To cover an area with innumerable observations of dip and strike, however carefully taken and noted on the map, is not geological mapping in any sense of the word, and may be a mere waste of time since both strike and dip faults, unconformabilities and lateral variations may never be detected by such an amateur method, and even pitches and dome structures may not be recognized if the ground be rough and much cut up by valleys.

Frequently the strata group themselves naturally, and the geological boundary lines to be followed are obvious, but in

very many cases the geological series consists of rapid alternations of two or three types of strata repeated over and over again, and it becomes necessary to select a few well-marked beds neither too near nor too far from each other and to map their outcrops as far as possible. It may be necessary to map the outcrops of many beds before one is discovered that persists and maintains its characteristics over a sufficient area; a prominent sandstone or limestone bed may thin, split up, and die out, and it may be necessary to cross to a lower or higher horizon and carry on the mapping of another band, which, though not so conspicuous where first observed, extends further and remains recognizable over a greater area than the bed first selected. It is better to map a thick bed or small group of beds than a thin bed, on account of the rapid changes due to lateral variation.

Where dips are steep it is not necessary to map separately horizons near to each other, as the structure will be made clear by the tracing of horizons from 500 to 1000 feet apart, but in areas where the strata are gently inclined and outcrops consequently become complicated and irregular, horizons separated by no more than 150 to 200 feet should be mapped. In an area with low dips towards the centre, and steep dips towards the margins, thin groups will be mapped in the central part, and the groups differentiated may be thicker and thicker in the outermost portions.

It is not sufficient to map a number of sections across the strike and join up the outcrops of the groups as observed, unless the ground is sufficiently bare to allow the outcrops to be seen all the way between each dip section. The selected beds or groups *must be followed and mapped* to detect any faults, changes of dip or strike, unconformabilities, or lateral variations. This method is, of course, somewhat more arduous, and takes up more time than sketching outcrops between the mapped sections in which the various groups have been identified, but it gives absolutely certain and indubitable results and brings out evidence which might be missed by making use of any less careful method. Coloured pencils will be found most useful in distinguishing the horizons followed on the field maps; in the finished map the areas between mapped horizons form the separate groups, which will be differentiated by well-contrasted colours to bring out the structure so that it can be understood

at a glance. It is then of very little moment whether or no the various groups are of the same types of sediment or not, so long as they are separated by mapped horizons and are distinctly coloured.

In open and bare ground as in Egypt, Persia, Baluchistan, and parts of India and Burma, there is seldom much difficulty in selecting groups for mapping and differentiation, but when vegetation is thick or the ground obscure the geologist may have considerable trouble in subdividing the part of the series that he is dealing with into such groups as will by their outcrops bring out the geological structure most clearly; it is in easy and open ground that the experience is gained that will enable the field-student to deal effectively with more obscure areas.

Eye Training.—One point is of the greatest importance to the young geologist who is undertaking the survey of new territory. He must train his eyes and learn to be as much as possible independent of his instruments. In bare and open ground, where one's position can always be ascertained accurately by taking cross-bearings upon known points, the tendency is naturally to rely upon such observations, with the result that when one is suddenly confronted with a densely-forested area, one may despair of ever making an accurate geological map of it, and may content oneself with the observation of a few dips and outcrops, the result being that a geologist of better training has eventually to go over the ground independently and do it all over again.

To begin with, the geologist must learn the scale upon which he is mapping, that is to say, he must become so familiar with it that he can judge a distance as seen on the ground before him and mark that distance upon his map, *without pausing to consider how many yards or feet it is.* To pace or chain a distance and then measure it off on the map by means of a protractor is no doubt often very useful, but there is no reason why the geologist should not train his eye by estimating the distance before he measures it; to be able to map any distance up to three hundred yards or a quarter of a mile without making any measurement is a very valuable asset to the field geologist. It is doubtful whether any one is so favoured by nature as to have a special gift for the estimation of distances, but the faculty can easily be acquired by constant

practice, and distances up to half a mile have been mapped in the author's experience with errors of not more than thirty feet. It is better, however, not to attempt to map distances of more than a quarter of a mile without some checking observations. It must be remembered always that estimates of distance are apt to vary greatly according to the light. The length of a coast-section with the tropical sun beating upon it is liable to be underestimated, while the length of a shaded road-section overhung by trees or a distance in jungly ground may easily be overestimated. Consequently the field-student should be constantly practising the transference of a distance as seen to his map under every condition of light or shade, afterwards pacing or chaining it and correcting any error he has made.

The next point in the training of the eye is learning to transfer observed angles to the map without the aid of a protractor, and with a very small margin of error, so that when bearings are taken with the pocket compass the observed angle can be sketched at once. This faculty can be acquired very quickly with a little practice; angles of 45 degrees, 30 degrees, and 60 degrees are, of course, very easily drawn, and the eye soon becomes efficient in estimating smaller, greater, or intermediate angles quickly. The error should not be more than 2 degrees, and provided that bearings are not taken from points more than a quarter of a mile distant, the map will not suffer in accuracy. When bearings are taken by prismatic compass the protractor must always be used and the angle laid off as carefully as possible, but in all ordinary field mapping with a compass by means of which the observer can read a bearing within 2 degrees, and with an eye practised in the estimation of angles on the map to within 2 degrees, mapping can be done at a rapid rate, and with wonderful accuracy, provided that each observation only includes a short distance. For practical purposes the distance should never exceed a quarter of a mile.

Having cultivated the faculty of estimating angles and distances with fair accuracy, the geologist will be able to make traverses with pocket compass, starting from a known point, and if possible finishing also at a known point. Such work, it may be objected, can never be entirely accurate, but it must be remembered that it is absolute certainty as to the

geological structure that is to be aimed at rather than meticulous attention to details of topography. A traverse by means of pocket compass of a mile or a mile and a half in length should not terminate with an error of more than forty or fifty yards. Bearings should be taken when possible by prismatic compass at distances of not more than half a mile; this will prevent any error from being made. If, however, no check readings are possible till the end of the traverse, there will nearly always be an error to correct. This should not be done at once, but a "correction mark" put upon the field-map (Fig. 14), and a new start made from the correct position as determined by compass bearings. Afterwards, when the maps

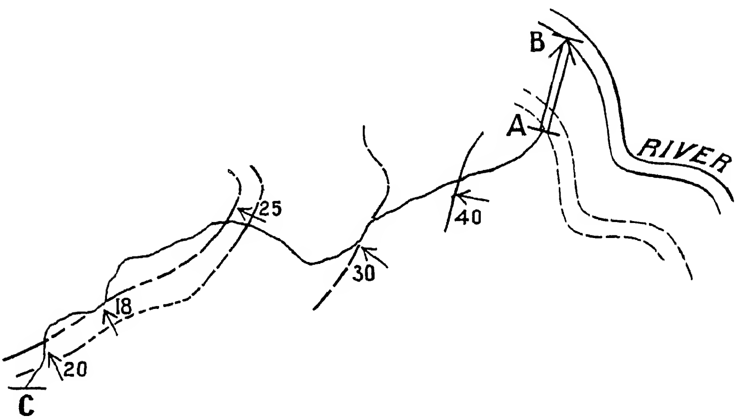

Fig. 14.—Sketch mapping in the field. C. Start of traverse; A. Finish of traverse; B. Point actually reached. ⇛ Correction mark. Traverse starts again from B.

are being inked in, *which should be done every day*, the error can be corrected. If the traverse has been very faulty, it will do no harm to make a second traverse starting from the other end; it is better to learn thoroughly the scale on which one is mapping than to depend entirely on one's instruments. It is not recommended that pocket compass traverses should be carried to a distance greater than three miles, and the beginner may find even that distance too long. In fairly open ground it will never be necessary to traverse any such distance without being able to check one's position by taking bearings from some point fixed by triangulation, but in forest land a traverse

without check of three miles or more may frequently be necessary. It is in bare or comparatively open ground that the field-student must teach himself to map with that accuracy which will be his only support when he has to deal with dense jungle, where no check readings are possible, and where the man who depends on his instruments rather than on his eye may feel quite unable to construct a geological map.

Another, but less important, faculty that should be cultivated is the estimation of the dip of strata without making any observation of it with a clinometer. This is a more difficult matter than the estimation of distance. When it is possible to look at a bed along the strike the matter is simple, and every geologist should be able to read the angle within 2 degrees, but it is often impossible to get such a view of the strata, and perspective views of dip are very deceptive. Constant practice, however, will enable the geologist to estimate dips very quickly and accurately, but it is not a method to be used constantly without checks. Whenever it is possible to take with a clinometer an observation of dip that represents approximately the true inclination of the beds, and this does not happen so frequently as the text-books would suggest, the instrument should be used, but at the same time the eye may be trained by estimating the angle before observation is taken.

Where dips are really of great importance, as in producing fields, or when a series of observations has to be made to enable a horizontal section to be drawn and the depth at any point to an oil-bearing horizon calculated, readings with an Abney's level or some similar instrument up or down dip slopes is by far the most reliable method. Strange as it may seem it is in this simple operation of observing a dip, probably the first thing in field work that the budding geologist learns, that most mistakes are made, and mistakes that may have very serious results. The tendency is *always* (and this applies to the experienced geologist as well as to the beginner) to exaggerate the angle of dip. Where bedding planes are not well-bared or exposed, it is almost invariably that dipping most steeply that is selected as offering the best surface, and unless a number of observations in the immediate neighbourhood be taken and averaged, the general inclination of the strata will be put at two high a figure in degrees.

Again, and this is especially true of Tertiary deltaic and littoral deposits, the dip of bedding planes may be at a very different angle from the general inclination of the series. Even where no false bedding can be detected, the strata probably have not been deposited in a horizontal position. Theoretically in fact, deltaic deposits are not deposited horizontally, and amidst the rapidly varying and quickly accumulated deposits of a Tertiary delta, where much of the petroleum-geologist's work will be done, it is by no means easy to make sure of the average inclination. Where folding is well marked, dips may change every few yards, and not by regular gradations, but often suddenly, so that quite apart from irregularities of original bedding the determination of the true dip at any point may be a very difficult matter. The only method in such cases is to make many observations on all sides, if there be sufficient evidence, and to take an average both as regards strike and dip, always remembering that the minimum inclination observed is more likely to be correct than the maximum. Strike is in any case more important than dip, and it is always as well to mark the strike of a bed, even when it is impossible to ascertain its true dip. It is because dips have to be averaged, and because it is inadvisable to give too much weight to a few isolated observations of the inclination of strata, that the method of estimating dips by the eye alone is frequently sufficient for all practical purposes.

In recording on the map an observation of dip, the point of the arrow should be marked as nearly as possible on the spot where the observation was taken.

Surveying in Jungles or Forest Land.—Lack of evidence is always the greatest difficulty in the way of making an intelligible and accurate map, and it is in the making of an intelligible and accurate map where evidence is meagre, that the experienced geological surveyor proves his ability. Any one can map strata that he can see exposed, but where exposures are few, or perhaps entirely wanting over miles of country, new methods have to be devised, new kinds of evidence have to be studied, and nothing may be too small and insignificant to give some hint as to the strike or dip of concealed strata. Unless evidence be studied minutely in more or less open ground—such matters, for instance, as the colour and texture of soils, the vegetation that grows on different varieties of deposit, clay, sandstone,

limestone, as the case may be, outcrops of water or petroleum—the key to the structure of obscure or wooded country may be lost.

One frequently sees it stated that there are "indications of petroleum" in a certain district, but that "it is impossible to ascertain the geological structure, as the ground is too densely clothed with vegetation." In other words, the geologist has been unable either from want of time, want of sufficient care, or the lack of reliable methods of surveying, to determine the geological structure. With the single exception of alluvial flats so vast in extent that the particular area, the geological structure of which is in question, is too far from any of the margins where reliable evidence can be obtained, there is no part of the world's land surface where such an impossibility exists. An ice-sheet may be considered as an exception to this, but it is hardly to be regarded as a land-surface.

Alluvium acts as a sponge, wiping out all direct evidence, though where belts of alluvium are not very large, their very presence may furnish valuable negative evidence; but no other covering, whether of glacial drift, blown sand, peat, vegetation, or coral terrace, is sufficient to prevent some details of geological structure being found somewhere. It is with the dense vegetation difficulty that the petroleum-geologist has to deal in many parts of the world. Tropical forests, such as those of South and Central America, or the bamboo jungles of India, are perhaps the most disheartening areas in which to attempt geological mapping, but it can be done; geological structure can be elucidated, and maps, not in great detail or of great accuracy, but at least reliable, can be made even under such conditions. The secret, if secret it can be called, is simply the adapting of one's methods to the particular work that is in hand. A completely accurate map is perhaps an impossibility without great expenditure of time and money in trace-cutting and land surveying, for which the geologist may not be able to spare the time, nor in all probability will he have the necessary instruments, but a sketch map of sufficient accuracy can be pieced together by careful, if at times laborious, work, just as a sketch map may be made anywhere without triangulation. It is here that the observer, who has thoroughly mastered his scale and can map accurately on pocket compass traverses, has the advantage over those who are, so to speak, tied to their instruments.

If there be any road or coast-section crossing or skirting the area to be surveyed it must be examined and mapped in detail first, copious notes being taken of the characteristics of each bed, such as the presence of pebbles or nodules and their natures. In a road, even where there is no section in side cuttings, it is possible to glean a fair amount of information. For instance, those parts underlaid by clay can always be distinguished from parts where the underlying beds are arenaceous, and a sharp and distinct line between thick masses of arenaceous and argillaceous sediments can often be drawn where no actual exposure is seen.

Then the forest or jungle must be attacked as far as possible in the same manner as in the case of more open ground. It is presumed that there is no topographical map available, that no hills from the summit of which compass bearings can be taken are to be seen, and that the courses of such streams and rivers as flow through the area are unknown. A coast, road, or river-section may give the key to the structure at once, but should no such section be available, or should it be discontinuous or obscure, it can only serve as a base-line on which starting points for traverses may be selected.

To begin with, if any group of hard or massive beds be present, the geologist should endeavour to follow it along the strike, noting the types of vegetation it supports, the colour and texture of the soil it forms, and whether under the weathering processes peculiar to forest land it is capable of standing out as a marked feature. In all thickly forested country there must be a fairly heavy rainfall, and consequently denudation of the surface will be fairly rapid in spite of the protection afforded to the soil by the vegetation. An arenaceous group in these circumstances, however soft and loosely compacted the strata may be, will always tend to form hills and high ground as contrasted with argillaceous strata. Much of the rainfall is absorbed by the porous arenaceous rocks to be thrown out as springs at the foot of dip-slope or escarpment, whereas an argillaceous outcrop absorbs little of the rainfall, but causes it to flow over the surface, thus favouring sub-aerial denudation. Consequently the outcrop of an argillaceous group among arenaceous rocks will almost invariably be marked by a valley or belt of low ground, however tough and hard the material may be, and an arenaceous group among clays will stand out as

a ridge, however loosely compacted the strata of which it is composed. In bare and open ground, where the rainfall is not heavy, the relative porosities of the strata do not have such a marked effect upon the contours of the surface.

The mapping of surface features, therefore, often becomes very important and of the greatest help to the geologist, though it must not be relied upon unless confirmed by other evidence such as the nature of the soil. Where denudation is rapid it may produce a complex system of ridges and valleys that have little or no relation to the strike and dip of the strata; in a thick series of clays in which the physical characters of different bands differ very slightly, an irregular and complicated drainage system quite irrespective of geological structure may be established, and the contours of the country where they can be observed, *e.g.* in areas planted with sugar-cane, may be sufficient to show that the strata are argillaceous before the soil has even been examined.

The angle of dip has also to be considered when features are being mapped; the greater the angle, the more clearly marked will be strike features, and where the strata are practically horizontal, outcrops naturally become very irregular and the following of them in undulating forest land may be simply a waste of time.

Having selected a group of strata that seems likely to form good strike features, and that is dipping at a sufficiently high angle where it is observed in the base-line section on coast-line, road, or river, it should be followed as far as possible along the strike. Exposures may be few or entirely wanting, but by studying the soil and the vegetation it may be possible to follow a group for great distances. The occurrence here and there of loose fragments of a hard rock, *e.g.* a calcareous sandstone, along an ill-defined ridge, may enable an outcrop to be picked up and mapped for miles till a river valley cutting across the strike gives an exposure and allows an observation of dip to be made. Once an horizon has been traced through the area to be examined the following of other horizons becomes a much easier task, and a fairly complete geological map may be constructed from evidence which approached by any other method would throw very little light upon the geological structure.

As a rule it is better not to follow the courses of streams at first, at least not until their general directions are ascertained.

If their courses be tortuous the mapping will be very tedious, and perhaps will result in the discovery of little evidence, while alluvial flats may be encountered to the discouragement of the observer. Where steep dips give evidence of flexuring on a considerable scale, however, the courses of streams or rivers can usually be resolved into "consequent" portions, *i.e.* across the strike, and "subsequent" portions, *i.e.* along the strike; and even where no exposures are to be seen, the evidence from the directions of drainage taken in connection with the orientation of ridges and hollows may give valuable evidence as to the strike of the series.

In following up outcrops or traversing across the strike, the geologist must map by "dead reckoning" with his pocket compass, using his map case every fifty yards or so to mark his track. Where the jungle is thick and has to be cutlassed to allow passage, if two men be kept in front of the observer at intervals of from 10 to 20 yards the mapping of track can be simplified by omitting many of the minor turns and twists inevitable when marching in forest land. It is not recommended that traverses of more than one mile be made at first, while three miles is as far as anyone is likely to be able to traverse by dead reckoning with any degree of accuracy; the writer has found that a traverse by pocket compass of four or five miles in forest land is inadvisable unless it is to a known point, or to a point the position of which can be ascertained by taking compass bearings.

The time required for simple mapping of the route taken, without study of geological data, will vary greatly according to the nature of the ground. Where there is not much cutlassing to be done and slopes are not too precipitous, one mile an hour is a fair average pace. In difficult country and where many observations have to be made the pace may be much slower.

Checking a traverse can only be done by making it a "closed traverse," coming out to some point along a road, river, or coast-line where the position can be found, or by making another traverse from a different starting point to the same final point.

In any case where the geologist fails to keep his track mapped and does not know his position, he should map on a new sheet of paper or in a note book, and either begin a

fresh traverse from his unknown position to reach some point which he can fix or recognize, or take a compass direction and keep it as straight as he can out to road, river, or coast-line. It is always better, however, to follow an outcrop, if one can be recognized and followed, than to map track across bedding.

It may seem that these methods are very rough and uncertain, and there is no doubt that the geologist when he first undertakes work in tropical forest will make many faulty traverses before he becomes master of the scale on which he is working and capable of traversing forest up and down hill, in and out of creeks and gullies while keeping his dead reckoning with accuracy, but there is no other method that will yield results so quickly, and at the same time develop confidence in the observer. To map with theodolite or plane table in the forest, cutting traces and chaining distances is far too cumbrous and slow a method, and can only be justified when the area to be examined is very small or when the exact position for a test well is being determined.

In jungle work where evidence is very scanty the geologist must be continually on the alert: nothing is too insignificant to be noted. Every change in the colour of the soil, every ridge that does not run parallel to the drainage channels, every occurrence of loose pebbles or nodules should be noted and the note marked clearly on the map. Similarly changes in the nature of the vegetation, if they are sudden, should be mapped. An exposed section may make clear the reason for such a change, and a very valuable piece of evidence may be added to the geologist's store of accumulated data. In Trinidad the Cretaceous formation, which lies unconformably beneath the petroliferous Tertiary Series, has frequently been recognized by the colour of the soil and the nature of the vegetation, when no exposures of the strata were to be seen. When exposed the strata are often very similar to some of the Tertiary deposits, but the soil formed by the disintegration possesses some pecularities which distinguish it from that formed from any of the Tertiary strata. Much of the Cretaceous formation has been prospected for petroleum by observers who have not learnt to distinguish it from the overlying Tertiary rock.

In clay ground the different tints induced by weathering processes have often proved of the greatest value, and have

enabled different bands to be mapped with accuracy. The black soils of a marl outcrop contrast so strikingly with the red or yellow soils derived from a clay that there need be no hesitation in mapping them separately. Again, "outcrops of water," surface springs, or damp ground marked by the occurrence of water-loving plants and trees often enable the observer to draw a boundary line which will be found later to coincide with the outcrop of a porous stratum.

Excavations.—The making of excavations to ascertain the nature, dip and strike of strata is sometimes, but very rarely, necessary. False evidence obtained by this method has often to the writer's knowledge led observers to make very serious and sometimes even ludicrous mistakes in their interpretation of geological structure. It must be remembered that in forest land, especially in tropical countries, disintegration of the strata extends for a great distance from the surface, often upwards of thirty feet, and in hilly ground surface-slip in partially disintegrated rock causes an astonishing amount of modification in the position of bedding planes. Root growth also disturbs the strata for a considerable distance. The result is that it is very difficult to select a spot for digging a trench where really reliable evidence will be obtained without excavating to a great depth. Small pits and trenches are liable to be dug into displaced or disintegrated beds, and it will readily be understood what confusion may arise through accepting the false evidence obtained by this method. It is only natural that the observer, having been at the expense and trouble of having a few excavations made, should attach more importance to the evidence obtained from them than to the possibly more obscure, but certainly more reliable, evidence that he has obtained by mapping outcrops or by the examination of natural exposures. And thus he may acquire an entirely incorrect idea of the geological structure.

There is something to be said for the digging of a few pits or trenches when it is done in connexion with the mapping of outcrops, but to depend on excavation alone to obtain evidence is to court disaster. In mapping some 500 square miles in the island of Trinidad the author only made use of specially dug trenches some half dozen times, and then it was to settle some detail rather than for general purposes of mapping. Some cuttings on roads in that Colony are

sufficient to prove what startling changes in strike and dip, and even inversions, in the soft Tertiary strata are due to surface slip.

If it becomes necessary to make an excavation, it is important to select a spot where evidence should be obtained without digging deep, and where such evidence is likely to prove reliable. The bottoms of valleys are naturally to be avoided, and also the tops of hills, hillocks, or plateaux; in the first case there will probably be a great accumulation of surface wash (Fig. 15), while on the tops of hills there may be a great

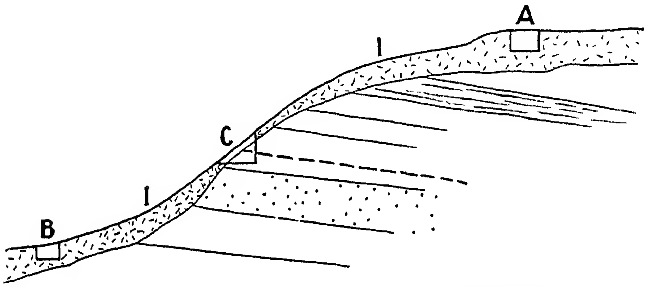

FIG. 15.—Excavation for dip evidence. 1. Disintegrated strata or surface wash.

thickness of completely disintegrated rock. At the top of a sharp ridge or hillock, or just beneath its summit (Fig. 16),

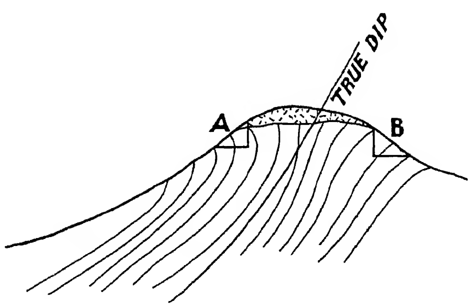

FIG. 16.—Surface curvature, giving false dips at top of ridge.

surface curvature may vitiate the accuracy of the observation although the strata may be obviously in situ, and at the bottom of such a ridge water may collect so rapidly as to hinder the digging. Half-way down a steep slope, especially if the slope is at a high angle to the probable line of strike, gives the best

chance of a reliable exposure, while the work of making the excavation will be easier, and the trench or pit can be kept drained and the exposed rock allowed to weather if the bedding is not apparent at once. In many varieties of Tertiary strata it is easier to detect the bedding planes after a certain amount of weathering has taken place, so that the keeping of an excavation free from water is a distinct advantage. But even with such a favourable spot selected, false evidence may be obtained if the strata be largely argillaceous. It is among the alternations of arenaceous and argillaceous beds, and where bands of hard rock or nodular concretionary bands are present that the best results are obtained from excavations.

Where flexuring has been intense, small minor folds or wrinkles may be occasionally present in a monocline far from any important anticlinal bend. This may lead to an incorrect reading of the geological structure if the observer relies upon excavations for his evidence. Fig. 17 shows a case that has

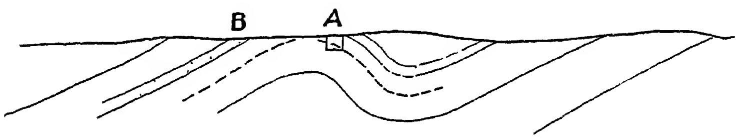

Fig. 17.—Obscure ground local flexure giving a false idea of general structure.

actually come under the writer's observation. The ground was low lying and evidence was very scanty; only at the points A and B could evidence of dip be obtained. The minor pucker disclosed by making an excavation was taken as being the crest of a great anticline, and as the strata on both sides were entirely argillaceous, and gave no evidence at all that could be considered reliable, the error survived for a long time, till field work in neighbouring districts proved the structure to be entirely different. But for this one unfortunate excavation no mistake would have been made.

In all field work in forest ground, as soon as the general structure has been ascertained, the more detailed mapping of stream sections should be undertaken with a view to getting as accurate an estimate as possible of the thickness of strata exposed, and making sure of the horizons of any oil-bearing strata that have been discovered. Should an anticlinal or dome structure with gently-dipping flanks be indicated, the following

of outcrops well down the flanks should be attempted before the inner and central portion is attacked. By this means faults will be more easily recognized and the structure will be more clearly and certainly delineated, and with less chance of error than if the lower zones exposed nearer to the crest are examined first. Where a very sharp flexure is indicated it will be best to follow and map the crest first, as by this means any pitches of the flexure that may be present should be detected and the relation of surface indications to the crest will be made clear. Afterwards, prominent beds on either flank can be selected and their outcrops traced, and if possible correlated on the two sides. Where anticlines are sharp, it is obvious that the position of the crest is the most important matter, and its trend must be mapped as carefully as possible, while where dips are gentle and flexures broad and comparatively speaking flat, the general form, asymmetry or pitches are of much more importance than any mapping of a crestal line, which, at the best, can only be marked approximately.

Lateral variations, which may be the cause of considerable difficulty in bare and open ground, become much more serious troubles to the geologist in heavily-wooded country, but if the area be examined systematically, a general idea at least of such variations should be obtained. Correlations cannot always be established with certainty, and the field-student must not expect to be able to correlate the two sides of any anticline in detail. The subdivision of the series into groups may even be impossible in some cases, except locally, but the attempt to subdivide should always be made; the construction of a new road through the forest may eventually furnish excellent evidence in side cuttings, and may enable a correlation that has been commenced to be carried to completion and settled beyond doubt. The mapping of any bed locally, even if it cannot be carried far, is always advisable, but the extension of dotted lines, indicating uncertainty as to an outcrop, between the points where the mapping of outcrops has terminated, when it has not been proved that the outcrops represent the same horizon, is to be deprecated.

Generalizations on insufficient evidence are above all things to be avoided; it is better to leave points with regard to correlation unsettled, and to say so definitely when reporting, than to force evidence to support a conclusion, however brilliant,

which is not absolutely certain. In cases where there is some doubt as to the meaning of such evidence as has been collected, a doubt that leaves the geological structure a matter of uncertainty, a process of elimination should be employed, and every structure possible in the particular circumstances tried and tested both by map and section. It will always be possible to reduce possible explanations to two or three, and the ground must not be quitted till sufficient evidence has been obtained to enable the geologist to decide as to which explanation is the true one From the map, whether completed or only half finished, the various possible explanations can be deduced, but it may be necessary to return again and again to certain parts of the area to settle points which will tilt the balance towards one or other of two alternative readings of the geological structure. No mistake in structure is allowable, and none should be possible if reliable methods be employed in the survey.

Ratio of Boundary to Area.—In all mapping, whatever be the nature of the ground, it is from the number of miles of geological lines drawn that we get the clearest idea of the efficiency of the geological survey. The area of land surveyed in a given time is no test of the ability of the geologist, but the ratio of linear miles of geological boundary lines drawn to the square mile of area mapped shows at a glance whether evidence has been scanty or not, and is the most certain criterion of the care with which the mapping has been done. This ratio may vary from fifty or sixty miles of boundary to one square mile of area, in very complicated and well-exposed country, to perhaps two to one in obscure and wooded ground. In the simple geological work of a Tertiary oilfield the ratio will seldom rise above 7 to 1. From 400 to 500 miles of geological lines represents a good year's work for any geologist, allowing time for the necessary indoor work, and it will be found that this will hold good in any country and in any kind of ground, bare or forest-grown.

To sum up, in ground thickly-clothed with vegetation the geologist must often be content with a map by no means complete or accurate. Mistakes in accuracy will doubtless be made in the mapping and need never be worried over, so long as no error is made with regard to structure. Should active development work follow the geological prospecting of an area,

details of mapping can always be corrected as the ground is opened up and new sections on roads and in excavations on sites for tanks and buildings are laid bare. The map can always be added to and improved in details, but if the structure be incorrectly delineated, the responsibility for the opening up of a field expensive to work and incapable of yielding results of commercial importance may lie at the door of the geologist. Thus, it is not till there is no doubt whatever about the geological structure that the geologist has any right to speak favourably or unfavourably of any new field: by advocating development work without knowing what is to be tested by the drill, or why, the geologist will class himself with the wild-cat drillers of a former generation or the company-promoting experts from whom the commercial world and the unfortunate public have suffered only too severely and too long.

It is naturally in thickly-wooded country, where at the best little can be known till development work has begun, that the greatest probability of ill-advised speculation is afforded, and consequently the more obscure the geological structure and features, the more cautious the geologist must be in making up his mind on the problems before him, and the more certain must he be of the main facts before he dare venture upon writing a report.

To visit a few oil-shows, to dig a few pits in search of evidence, and to make a few observations of strike and dip may suffice for some experts, but no one whose ambition is to take rank as a geologist can afford to advise a commercial company upon the results of what are merely preliminary observations. If the area be tested and failure attend the attempts to strike oil, to shelter oneself behind the alleged capricious nature of that liquid is merely to call attention to the uncertainty of one's own field work, and the unreliability of one's own mental processes.

CHAPTER X

(For Beginners)

INDOOR WORK

Though it is in the field that the real work of the geologist is done, systematic and careful indoor work must follow if the full fruits of his toil are to be garnered. In the last chapter the author has endeavoured to explain the methods that he has found most effective in field-work under different conditions; it remains to indicate the lines upon which the necessary indoor work can be conducted with the greatest facility, in the hope that the field student may find in them some hints that will prove useful to him in the more irksome but no less important portion of his task.

When the field work in any district has been completed there must be a gathering together and correlation of facts, a reviewing of evidence, and a preparation of finished maps and sections, all of which can be done much more effectively in some office or headquarters, where there are greater facilities and better appliances for indoor work than the geologist will be able to carry with him in the field, however elaborate his equipment.

As a rule it will be found that two months of actual field work, during which an area of from twenty to fifty square miles, according to the nature of the ground, should have been mapped, will necessitate three weeks of indoor work. The author has found that this proportion of indoor work to field work holds good both in bare ground where twenty or thirty linear miles of geological lines are mapped in a square mile of area, and in obscure or densely forested land where the ratio of boundary to area is 2 or 3 to 1.

Preparation of Map.—The first thing to be done is to prepare the finished map of the area on the scale upon which

the field work has been undertaken. This, if there are many corrections to be made for errors in traverses by dead reckoning, will be a matter requiring considerable care, and it may be necessary in order to fit the traverses together with accuracy to make a rough copy of the map first. If the area proves to be of little importance, or if the evidence collected is insufficient to make a large-scale map, a reduction to the one-inch scale may be expedient. In all preliminary work a map on the scale of one inch to the mile is generally quite sufficient to give a clear idea of the structure and the prospects of obtaining a production of oil. Again, where a large area has been prospected on the one-inch scale in search of localities worthy of more careful examination, the smaller scale is quite sufficient. But if the area is to be exploited and active development work is to follow the geological examination, a large-scale map is necessary, even though it may not be possible to put much evidence upon it as the result of the first geological survey.

In the finished map it may be necessary to omit much detail that has occupied a considerable time in mapping. To introduce detailed work where it is not essential will have the effect of confusing those who, having little technical knowledge of geology, may yet have to study the map and master its significance. The map should be as simple and clear as possible. The strata should be grouped and coloured distinctively, so that every essential point in the geological structure is brought out. "Colour without line" is not allowable; that is to say, every group distinguished by a separate colour must have a clearly defined boundary up to which the colour is brought. Mapped lines of outcrops without special colour may be introduced locally in the midst of any group if any object is to be gained thereby, such as showing sudden changes of dip or explaining the broadening or narrowing of outcrops owing to the contours of the surface. Similarly it may be expedient to map a fossiliferous horizon in some group, without colouring it specially. Where dips are gentle the groups of strata coloured must be comparatively thin, but in an area where the rocks are highly inclined it is not necessary to colour specially more than three or four groups, and they may be of considerable thickness.

Dip arrows and the conventional geological symbols should

not be distributed too thickly about the map. There must be enough to make the structure clear to any one without an intimate acquaintance with geological work, and any line of section to which special reference is to be made should have a large number of dips noted, but the map must not be overloaded with such symbols. It will be found advisable to use some characteristic and prominent symbol for surface indications of petroleum, and if the map be on a sufficiently large scale the words "gas," "oil-seepage," "asphalt," "manjak," or "ozokerite," as the case may be, can be written or printed beside the symbol. The author has always used a diagonal cross to mark surface indications, making it rather larger and more prominent than the symbols indicating the inclination of strata. A symbol indicating the direction of the pitch of a flexure is often useful.

Every map should be accompanied by a tablet showing the groups of strata with their distinctive colours and their order of deposition, and all symbols used.

True north should be shown on every map, but it is not necessary to indicate magnetic north.

Sections.—When the map has been completed it is often useful and sometimes essential to make one or more horizontal sections through the area. These cannot be made till the map is finished. They are very valuable as giving an idea of the structure to those who are not capable of reading a geological map, though they are not necessary to the experienced geologist.

It is a common mistake of the amateur or the untrained geologist to draw sections through a property or concession without making a geological map at all. Such sections, though interesting as giving evidence of the ideas of their authors as to the geological structure of the area, are generally useless, and are almost invariably misleading. Till the area has been carefully mapped the drawing of horizontal sections with any measure of accuracy is practically impossible.

Horizontal sections should always be drawn on the same scale as the map, and except in very rare instances for special purposes the vertical and horizontal scales should be the same; for it is obviously impossible to give the true dip and thickness of strata, or the true hade of the axis of a fold, if the vertical scale be different from the horizontal.

In making a horizontal section the contour of the surface must first be sketched from aneroid readings, topographical surveys, or any other evidence that is available. If there are no ascertained data to go upon, the surface must be sketched by guess-work. Except in very hilly ground errors will have very little effect, as the depths beneath the surface that will have to be considered will probably be very much greater than the irregularities of the surface, and will make the latter appear quite insignificant.

A base line is then drawn at a sufficient distance below the line representing the surface; there is no reason why this base line should be made to coincide with sea-level or any height above or depth below it. Then from the line of section as

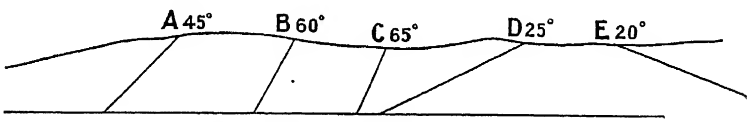

FIG. 18A.—Wrong method in section drawing.

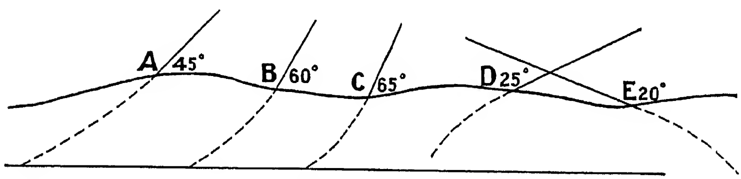

FIG. 18B.—Right method.

drawn on the map the positions of geological boundary lines and dips of strata as noted are marked on the base line and projected to meet the line representing the surface of the ground. The angles of dip are then drawn *upwards* from the surface and not downwards (Fig. 18). The reason for this is that at the surface where the dips are noted the angles of inclination are only observed for an infinitesimal distance. The first thing that one learns in drawing horizontal sections to scale is that all inclined strata are parts of great curves, and that the dip of no bed continues for any considerable distance downwards without changing. The lines representing the bedding planes are then continued downwards, care being taken to keep the thickness of each group constant, unless variations in thickness have been actually proved to exist. It will be found at once that

dips as observed are almost invariably too high to make the drawing of a section an easy matter, and that if there be no faulting and dislocation of the strata the minimum observed dips will have to be accepted. This is to some extent a concession to convention, but, that notwithstanding, it throws a striking light upon the errors into which one may fall by a blind acceptance of the dips observed at the surface as being constant for over large distances downwards, and the danger of depending on a few observations of dip for the elucidation of structure. It is obvious that when it comes to the measuring of the thicknesses of groups of strata and calculating the depth to oil-bearing horizons throughout a field, errors made by noting maximum dip may be sufficient to detract in no small measure from the practical value of one's work.

There are naturally many details in a section which must be almost purely imaginary, and such points as the underground courses of unconformable junctions and fault planes cannot be indicated with certainty unless there is direct evidence from boring journals to assist the geologist.

The horizontal sections, if carefully constructed, will be of great value in checking the thicknesses of groups as obtained by measurement on the map, but the use of a section is rather to explain the structure to those who have difficulty in reading geological maps than to give data for the precise development work in an oilfield. When evidence from a number of oilwells is available, sections can be made on a much larger scale than that used in mapping, and every petroliferous horizon can be shown at its true depth; the field-manager will then be able to adapt his methods to the end in view in each well, knowing exactly at what depths water must be shut off and where oil is likely to be struck. In new untested fields such accuracy is unfortunately very seldom possible.

Vertical Section.—After the horizontal section has been completed it is often expedient to construct a vertical section of all the strata exposed in the area, leaving room below for the strata to be proved in the drilling. The vertical section must be drawn to scale, but a much larger scale should be employed than that on which the ground has been mapped. The groups of strata, coloured as on the map and in their relative thicknesses, will be marked clearly in the vertical section, and the horizons of all fossiliferous beds and oil-bearing bands observed

will be noted as accurately as possible. It is advisable also to mark the initial horizons of any wells that have been drilled, or that it is proposed to drill, so that it will at once be apparent what horizons have been or can be tested.

Palæontological Work.—Any fossil evidence that has been collected must then be gone over and compared with previous collections or books of reference in order that any. organisms of importance in establishing stratigraphical horizons may be recognized. Where palæontological evidence is abundant, as for instance in Burma, some such method as that described in Chapter VII. may be made use of, but as a rule a less elaborate system will be quite adequate; it is seldom that fossil evidence becomes of any great importance till a great mass of material has been collected.

Petrographical Work.—It is but rarely that petrographical work is of much value in an oilfield till after it has been at least partially developed, but there are often points that can be settled by the use of a microscope, and that may eventually prove of vital importance. The examination of oilsands may furnish very valuable evidence, as it is often possible to identify different sands by their mineral contents. This is especially important when an unconformability is suspected but has not been proved. Sands that appear very similar may be from formations of different ages, and may contain minerals which enable them to be distinguished at once; the heavy minerals are frequently the most useful in this respect. The presence of Kaolin or decomposed felspar may be a point of great importance, as in some parts of Burma in separating post from pre-volcanic strata.

The determination of the extent to which a limestone has been dolomitized is another question that may be of vital imporance in oilfields where the petroliferous rocks are calcareous. All these matters can be dealt with by means of a petrographical microscope without the necessity of making any chemical tests, and though that instrument can hardly be regarded as an essential part of the petroleum-geologist's equipment, it may be of very great use when other evidence fails and only petrological work can be depended on to solve some difficult problem. There is, in fact, no department of geological work that cannot

in certain circumstances be brought to the aid of the geologist who is engaged in the study of oilfields.

Report Writing.—With the completion of any palaeontological or petrographical work that may have had to be undertaken, the geologist's task is practically over for the time being; it only remains to write a report upon the area examined. It is in the field work and the preparation of map and sections that the real work of the geologist has been accomplished, but by a very natural irony it is the report that will receive the most attention, and the young geologist may be assured that for one man who will study his maps, ten at least will read his reports and interpret them in their own fashion. Chairmen of Companies, Managing Directors, Technical Experts, Company Promoters, and even a small section of the shareholders and the speculative general public all attach value to a report rather than a geological map, and consequently it is essential that great care should be taken in the writing of it. As with most practical geologists, among whom the writer has no further ambition than to be classed, the hammer is mightier than the pen, the writing of the necessary reports may be not only difficult but irksome.

In the report on a new area, a presumed but untested oilfield, brevity is the first essential. The geologist, if he has sufficient time, should write out his report three times, each time making it shorter by cutting out all that does not seem absolutely necessary. Looked at from this point of view it is wonderful how much "padding" can be detected in even a workman-like and concise report.

Clearness is no less essential. Technical geological terms should be eschewed as far as possible, as it is probable that of those who read a report few will have more than a smattering of geological knowledge. It is not difficult to explain in simple language all that can be conveyed by sesquipedalian scientific phraseology. Again, it is not enough that the writer is clear in his own mind upon a point; he must set it down so that the reader cannot fail to be clear in *his* mind as to what is meant to be conveyed. This is not such a simple matter as it appears at first sight. In correspondence with reference to a report or the ground with which it deals, the geologist's statements will be paraphrased and unintentionally misquoted, and some day a statement which the writer considered impossible to misconstrue

will come back to him distorted out of all recognition and labelled as his opinion. Therefore short, crisp sentences, without conditional clauses, should be the rule.

Graces of style and the neat turning of phrases are to be avoided; it is possible to give a literary flavour to scientific work, as many of the greatest geologists, from Hugh Miller onwards, have taught us, but it is not literature that is required from the field geologist, but facts. If in reading over the draft of a report one comes upon any sentence with which one is particularly pleased, the wisest course is to cut it out at once. Be literal rather than literary.

The point most essential of all is to stick to facts. Opinions *must not be given on any points of importance in the geology of the area examined.* It is, of course, impossible to avoid giving an opinion upon such a question as whether an area is sufficiently promising to warrant development work being undertaken or not, but in dealing with questions of structure, lateral variation, thickness of oil-bearing strata, depth to be drilled, etc., no mere opinion will suffice. If the certified facts cannot be given, the geologist must say so clearly. "To the best of my belief," "as far as I could ascertain," "in my opinion," "it seems to me," and the numberless similar phrases should be tabooed. Indeed, the geologist will do well to shun the use of the first personal pronoun as much as possible, and to write his report in the third person. The report will read better and will appeal more forcibly to both scientific and commercial readers if the writer does not intrude his personality, but allows the facts as ascertained by him and set forth in map, section and report to speak for themselves.

The ideal report must be partly descriptive; it must explain the map to those who may not be able to read geological maps. It must call attention to the points of greatest importance in the structure, etc., but it is quite unnecessary to describe and explain the map in detail. Geological structure can be dealt with very briefly: the map and sections should be sufficient with a few sentences of explanation. Enough must be written concerning the methods of mapping employed and the nature of the strata examined to show the care with which the survey has been conducted. The distinguishing characteristics of different groups of strata mapped must be mentioned, but long lithological descriptions are unnecessary.

Evidence of the presence of petroleum should be treated separately and at greater length, for much, and in some cases perhaps undue, importance will be attached to such evidence by those for whom the report is written. It is always necessary to prove as conclusively as possible the petroliferous nature of the series that has been studied geologically, and the conditions under which surface shows of petroleum occur afford very valuable hints to the expert or technical adviser and the field manager.

A comparison of the field with other areas as regards structure, stratigraphy, and surface indications, especially if those other areas are producing fields, may be introduced with advantage in this section of the report in order to give some idea of the significance of the evidence, but any canvassing of the probabilities of proving a valuable field is better kept for the final section.

It is always best to divide a report into clearly defined sections, and to keep each piece of evidence rigidly to its own section. These sections may again be subdivided, and the report should be headed by a page showing the divisions and subdivisions, so that any part can be referred to with the least trouble and delay. A convenient form, which the writer has found to meet most cases of new and untested fields, is as follows:—

Report on Concession.

I. Introductory.
II. Formations and Strata.
III. Geological Structure.
IV. Oilshows.
V. General Conclusions and Recommendations.

Fig. 1. Map of Concession and surroundings 6 in. to the mile.
Fig. 2. Horizontal Section . . . . do.
Fig. 3. Vertical Section . . . . 2 in. to 100 feet.

In the first section the position of the property or concession is briefly described, and the nature of the ground, whether low or hilly, forested or bare. The methods of survey employed are explained and the work of any previous observers in the same area must be touched on.

In the second section the various formations exposed in the

area are described shortly in their stratigraphical relations. Each group of strata mapped and coloured separately is described and its thickness estimated, and the horizons of oil-bearing strata and fossiliferous beds are given. If fossil evidence be very abundant, it is better not to give it at length in this section, but to state the general conclusions arrived at from palæontological work, and keep a detailed account of it for an appendix to the report.

In Section III the structure as shown by the map and horizontal section is explained briefly, and the account may be subdivided into evidence of: (1) Flexuring; (2) Faulting, and (3) Unconformabilities, etc. as may be necessary.

A special section upon the indications of petroleum is only necessary when they are extensive and important enough to deserve careful description. If the "oilshows" are few and insignificant this section can be merged in Section II.

In the last section the general conclusions on scientific points must be stated very clearly and briefly: it is often advisable to number them, *e.g.*:—

(1) The strata are of the nature common to many oilfields, and give evidence of containing petroleum at intervals throughout a thickness of 3000 feet.

(2) The geological structure over the greater part of the area is unfavourable to a production of petroleum, but in the north-west corner of the concession is very favourable.

(3) The area of favourable structure is approximately acres, etc., etc.

Though the scientific reader will doubtless give full attention to the whole report, it is the last section, the "conclusions and recommendations" that will be studied most closely, and that will be quoted and canvassed by every one else; indeed, the earlier part of the report may merely be glanced through.

After the "conclusions" comes the "opinion" as to whether development work on the new field will be justified or not. If properly led up to, this opinion should appear inevitable.

Then, if a favourable opinion has been given, come the recommendations as to how the area should be developed. The sites chosen for test-wells should be described, and the reasons

for selecting them given. If locations have actually been marked on the ground and on the map, it is not necessary to deal at length with their advantages and disadvantages; the initial horizon of each test-well can be shown on the vertical section, and the position of each as regards geological structure can be given on the horizontal section.

The depth to be drilled in each case should be stated, as well as the nature of the strata to be drilled through, and any difficulties likely to be encountered in the drilling through the occurrence of water-sands, loosely-compacted sands, thick soft clays, or steeply-dipping strata must be mentioned.

Proximity to water supply, best means of access to the well sites, and difficulties in the way of road-making incidental to the nature of the country and strata should be touched upon: though these matters are hardly within the province of the geologist, any information about them will be of value to a field manager.

Finally, if the geologist has sufficient experience in oilfield work to justify him in so doing, the method of drilling which he believes will give the most successful results in the special circumstances, and the expenditure which he considers should be sufficient to allow of the test-wells being drilled in a satisfactory manner, may be indicated. On these latter points, however, it is well to use a wise caution. Unforeseen circumstances may arise to falsify estimates of expenditure, and it is better, unless specially requested to do otherwise, to leave all such matters to those who will have to be responsible for the practical development work.

It is a very simple matter when dealing with a new oilfield to write a favourable report in somewhat indefinite terms, dealing with such evidence as has been obtained in a general way, and not stating the reasons why any particular fact is regarded as favourable. Reports of this kind are very common nowadays, and may frequently be found in a prospectus. The geologist who wishes to establish his reputation for reliability must be careful not to fall into this style, which is fatally easy to acquire. The disadvantages of a new field should be stated as clearly as its advantages, and though the expert who does not hesitate to condemn a field upon evidence which he gives, and holds to be sufficient, is never so popular as he who can write a carefully safe-guarded report, which at the

same time gives the reader a highly favourable impression of the prospects of a field, in the long run the man who confines himself to the stating of facts, and has the courage of his convictions, will carry the most weight. A reputation for caution and even pessimism will be of more value to the young geologist than an ill-regulated enthusiasm which may have the effect of inducing capitalists and the public to sink large sums in fruitless expenditure.

Report on a proved field.—In reporting upon a field already tested and partially developed, the geologist has a much more complicated task. An accurate topographical map in all probability will be available, and the geological data must be noted upon it with great care. A larger scale than 6 or 8 inches to the mile will probably have to be employed, and the exact position of every well, drilled or drilling, must be marked. Then after the geological map and horizontal section have been completed, logs and boring journals must be consulted and every well projected on to the horizontal section, showing its initial horizon and the depth reached. The underground geology can then be added from the logs of the wells and a correlation of the oil-bearing horizons attempted. Where many wells have been drilled it is often possible to correlate every water-sand and every oil or gas-show throughout a field, and to draw contour lines upon the map showing the depths to an oil horizon at any part of the area. In some of the American fields, notably that Coalinga in California, this has been done with great success. When such accurate work is possible the required depth for each new well can be calculated from the elevation of its site and its position with regard to these contour lines, and the depth at which water must be shut off can be given with certainty, so that a field manager is enabled to save much expense by adapting his methods to the particular object aimed at and economizing in the matter of casing.

The report will require to be written on a different system; there must be a section dealing at length with the evidence from wells and the correlation of the underground strata. These, however, are matters not entirely geological, and can be undertaken by persons without any special technical knowledge. It is before a field has reached the producing stage that the services of a geologist are essential. After the map

and horizontal sections have been completed, and the confines of the field proved, the petroleum expert may take the place of the geologist.

When working in a producing field great caution must be exercised in taking hearsay evidence about the strata in any well and the shows of water at any horizon in it. The logs of wells are not always reliable, and even when kept with care too much is often left to the personal opinion of the driller. Strata are frequently incorrectly described, and two drillers may give different names to the same type of sediment. Boring records and hearsay evidence, therefore, must not be blindly relied upon. Not that the geologist will be intentionally misled by the practical workers in an oilfield—though cases of deliberate attempts to mislead the scientific worker are not altogether unknown—but the mind untrained in scientific work may not be able to convey or express information in such a form that it can be grasped accurately. From a report hearsay evidence should be rigidly excluded; it is better to leave a point unsettled than to rely, however slightly, upon second-hand information.

One point with regard to the writing of reports remains to be touched upon. It will frequently happen that the geologist in the course of his field work will establish, or obtain evidence about, some point of general scientific interest, and he will naturally be tempted to enlarge upon it in his report. In such cases the best procedure is to consider whether the scientific point in question is of practical importance in the commercial development of any particular field, and whether other members of a scientific staff working in the same interests will be helped in their investigations by the new knowledge acquired. If so, the evidence should be described briefly and the conclusion stated. Otherwise it is better not to overload a report with matters, however interesting and important from the scientific point of view, that have no direct bearing upon the practical finding and producing of petroleum. Appendices can always be written to a report to contain such results of the geologist's investigations as are of greater scientific than practical importance.

Reports are always subject to criticism, and as a matter of course always receive it, practical or academic, pertinent or impertinent, fair or unfair, and occasionally merely ignorant.

Any criticism is stimulating, or should be so, to the practical geologist, and in the majority of cases must be beneficial howsoever unfair it may be. The answer to it is in work rather than controversy. Theories may be promulgated, tested by the facts, and fall; fallacies often die very hard and may even be brought to life again unexpectedly, but the search for truth goes on, and the dealer in facts has in the end the victory over the critic steeped in theory who has not the advantage of first-hand acquaintance with all the evidence. Therefore the field-student in his writings should eschew theory and stick to facts, nor resent the spur of criticism however clumsily applied.

In these notes the author is conscious that he is setting forth, probably at undue length, a great deal of very obvious advice, which even the tyro in geological work in oilfields may stigmatize as common-place and banal. "These matters," he may say, "are merely common sense," in which he neither requires nor desires instruction. The author does not cavil at, but rather applauds such a dictum; each man must depend on his own common sense, and to teach geology from books rather than in the field is an academic absurdity. Out of the fruits of considerable experience the author has written in the last two chapters these notes, not claiming for them any originality, nor desiring to dogmatize, but hoping that here and there among them the beginner may find something that will help him in his practical work.

It may seem that the duties of a petroleum geologist have been made to appear samewhat elaborate and complicated. They may be, and indeed often are so; the geological work in an oilfield, especially in a Tertiary oilfield, is in itself simple, but to guide the development work of a petroleum company with complete success, without causing needless expenditure, and without having to admit failure now and then, may be very difficult. Every kind of evidence must be studied, every precaution taken, and every detail examined if certainty is to be arrived at. And that in very many instances practical certainty can be attained in oil-finding is the firm belief of the author, though years of laborious fieldwork and research under conditions not always of the most attractive may have to be accomplished before such a result is within sight.

A great field is opening up nowadays for the prospecting geologist, the man trained in scientific processes of thought,

and physically fitted to endure the hardships and discomforts of field work in those parts of the world where nature is not yet shackled by civilization. It is in tropical and sub-tropical countries that much of the earth's richest stores are to be searched for and won, and it is to him who can withstand unfavourable climatic conditions, under tropical sun, or in dark forest, on desert and barren hill, or in cane-field and plantation, that the prizes will fall.

In no branch of geological work is there a more promising field than that offered by the search for petroleum, and no commercial enterprise depends more for its success upon the geologist than the finding and winning of oil. The life of the oil-finder, with its travel in many lands, its contact with many races, and its frequent change of scene, is, taking the rough with the smooth, a thoroughly enjoyable one. To the sportsman—and every field-geologist should be somewhat of a sportsman at heart—there are moments that compensate one richly for the hardships incidental to the exploration of wild and little known country.

If this little introduction to the great subject of oil-finding be instrumental in turning the attention of the young geologist to the fascinating subject of petroleum, and be of service, in however slight a degree, in setting his feet in the path that leads to success, the aim of the author will be accomplished and his labour rewarded.

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